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THERMAL CONSOLIDATION IN A VAPOR-DOMINATED RESERVOIR

Cheo K. Lee and M. Nafi Toksöz
Earth Resources Laboratory
Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology, Cambridge, MA 02139

ABSTRACT

Thermal consolidation due to vapor production from a vapor-dominated geothermal reservoir with natural recharge from an overlying liquid layer is examined. When the vapor is extracted, the pressure declines and the liquid vaporizes as the liquid layer descends into the vapor zone. It is shown that the flow-induced pressure change is comparable to the hydrostatic profile for a typical production rate and that the subsidence is mainly from thermal compaction in the liquid-invaded zone. The total subsidence in the reservoir increases as the production rate increases but decreases as porosity decreases. The permeability variation only affects the reservoir life in such a manner that the processes are inversely proportional to the permeability change.

INTRODUCTION

Geothermal reservoirs are usually categorized as either liquid-dominated or vapor-dominated depending on steam saturation. The Wairakei field, New Zealand is a typical example of a liquid-dominated type where the maximum subsidence of $4.5m$ has been recorded (Bixley, 1984). The Larderello, Italy and Geysers, California are the largest geothermal fields of a vapor-dominated type. In the Geysers, only $14cm$ of subsidence has been measured(Lofgren, 1978). However, in the Travale field near Larderello, subsidence values of more than $40cm$ were observed(Di Filippo et al., 1995).

For thermal consolidation in liquid-saturated porous media, the governing equations have been derived with or without the coupling effects among the fluid, solid and heat (Brownell et al., 1977; Bear and Corapcioglu, 1981; Kurashige, 1989). These are based on the phenomenological relations for the behavior of the fluid and solid matrix. Lee and Mei(1995a,b) employed the theory of homogenization to deduce the governing laws for thermal consolidation in a liquid-saturated medium. Under the assumptions of the existence of disparate length scales and the periodicity of the medium, the global scale constitutive coefficients are determined by solving certain microcell boundary value problems for a given cell geometry (empirical or closure assumptions are not required). The governing equations are applied to the extraction of the fluid from a reservoir(Lee and Mei, 1996). In two dimensions, it is shown that the flow instability can be triggered at a Rayleigh number below the theoretical threshold for natural convection.

When vapor is extracted from a vapor-dominated reservoir through production wells, the pressure declines and regeneration of vapor is needed for continued exploitation. This can be achieved by either natural recharge from an overlying liquid layer or water injection. As water invades the hot vapor zone, vaporization of the liquid occurs at the interface. An important phenomenon during this process is reservoir deformation, which results in the subsidence. The reservoir may experience both swelling due to the buoyancy effect caused by liquid invasion and compaction due to thermal cooling of the rock matrix.

For cold water injection, Woods and Fitzgerald(1993) have studied the effects of the injection rate and the geometry of injection on the vaporization of a liquid front moving through hot porous rock. They showed that as the injection rate increases the vapor pressure and the temperature at the front increase, and the vaporizing fraction decreases. They also showed that, for a constant injection rate, the vaporizing fraction of water stays at the maximum level for a point source, reaches a constant value for a line source, and decreases to a very small value for a planar source. The vaporization of water in bounded and unbounded systems for water injection and/or vapor production has also been investigated by Fitzgerald and Woods(1995a). The vaporization of water in an one-dimensional vapor-dominated reservoir with natural recharge of vapor from a descending liquid layer has been considered by Fitzgerald and Woods(1995b) to study the variation of the vapor pressure, the vaporizing fraction at the interface and the downward movement of the interface. For higher vapor temperature, both the reservoir life(i.e., the time for the water-vapor interface reaches the reservoir bottom) and the vaporizing fraction become greater.

Fitzgerald and Woods(1995b) assumed that the pressure in the liquid region is hydrostatic. This assumption is valid only for production rates with an induced pressure gradient much smaller than the hydrostatic pressure gradient and might be too restrictive an assumption. We consider the simple model of an one-dimensional vapor-dominated geothermal reservoir considered by Fitzgerald and Woods(1995b) (shown in Fig. 1) with a vapor zone of thickness $\bar{r}$ and a liquid and condensate zone of thickness $(D - \bar{r})$ at the initial equilibrium state.

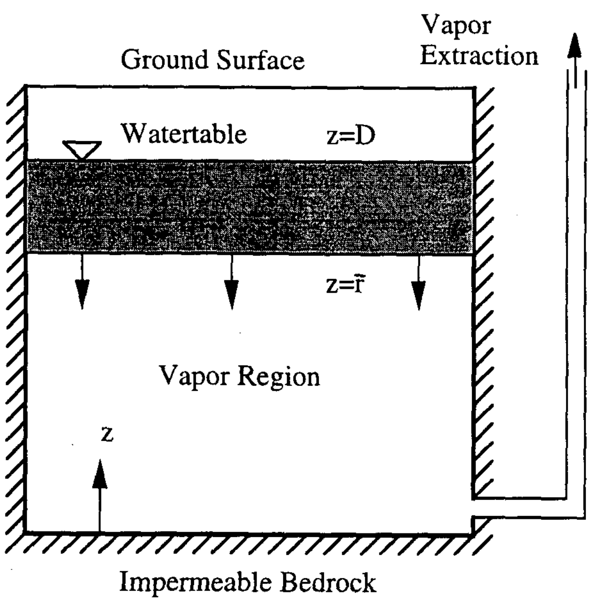

Fig. 1. A vapor-dominated geothermal reservoir with vaporization from an overlying liquid layer.

In this paper, we allow the production rate to be finite so that the induced pressure gradient in the liquid is not necessarily small compared to the hydrostatic value. Schubert and Strauss(1980) have shown by a linear stability analysis that the heavier liquid can exist above the vapor region if the medium permeability is sufficiently small. Supposing that the vapor is extracted from the reservoir through distributed wells, the pressure is assumed to be uniform in the vapor region. It is a fairly good approximation since the time scale for pressure diffusion is much smaller than the time scale for the interface to move across the vapor region, as will be shown below.

We assume that the liquid is incompressible, whereas the vapor obeys the equation of state for an ideal gas. The reservoir rock matrix is assumed to be relatively hard e.g., the consolidation equation(Lee and Mei, 1995a) becomes a steady form because the consolidation time is much smaller than the heat convection or diffusion times. Specifically, we examine the effects of the production rate, porosity, and permeability on the reservoir pressure and temperature, the vaporizing fraction, and the subsidence.

THE GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

Let ϕ and k denote the porosity and the permeability of the medium. Also let ρ_w, μ_w and u_w be the density and viscosity of the fluid and the seepage velocity, respectively, in the liquid region and, similarly, ρ_v μ_v and u_v in the vapor region. The location of the interface Γ is denoted by $z = r(t)$. The initial liquid zone, the liquid-invaded zone, and the vapor zone are denoted by $\bar{\Omega}_w(\bar{r} < z < D)$, $\tilde{\Omega}_w(r(t) < z < \bar{r})$ and $\Omega_v(0 < z < r(t))$, respectively. Initially the pressure is hydrostatic in the liquid zone and uniform in the vapor zone(e.g., $\bar{p} = \rho_w g(D - z)$ for $z \in \bar{\Omega}_w$ and $\bar{p} = \rho_w g(D - \bar{r})$ for $z \in \Omega_v$). In $\bar{\Omega}_w$ and $\tilde{\Omega}_w$, the flow-induced pressure is denoted by $\tilde{p}$. The total liquid pressure p^T is equal to $\bar{p} + \tilde{p}$ in $\bar{\Omega}_w$ and to $\bar{p} + p_{wi} + \tilde{p}$ in $\tilde{\Omega}_w$, where $p_{wi} = \rho_w g(\bar{r} - z)$ is the hydrostatic pressure due to water invasion.

Boundary Conditions on the Interface

The mass flux continuity at Γ requires (Fitzgerald and Woods, 1994):

$$\rho_w u_w - \rho_v u_v = (\rho_w - \rho_v)\phi \frac{dr}{dt}, \qquad (1)$$

where the seepage velocities are given by Darcy's law

$$u_{w,v} = -\frac{k}{\mu_{w,v}}\frac{\partial \tilde{p}}{\partial z}. \qquad (2)$$

Let F be the vaporizing fraction at Γ and M the vapor extraction rate from the vapor zone per unit time and unit area. From its definition, F is related to u_w by

$$u_w = \frac{\phi}{1-F}\frac{dr}{dt}. \qquad (3)$$

Combining (1), (2), and (3) we obtain

$$\rho_w u_w = -\frac{\rho_w k}{\mu_w}\frac{\partial \tilde{p}}{\partial z} = \frac{\rho_w \phi}{1-F}\frac{dr}{dt} \qquad (4)$$
$$\rho_v u_v = -M = \frac{\rho_w F + \rho_v(1-F)}{1-F}\phi\frac{dr}{dt}.$$

The heat flux continuity at Γ requires that the heat supplied to the interface from the liquid phase be equal to the heat carried away from Γ and the heat to cool down the rock invaded by the moving interface. At equilibrium the temperature profile with depth usually shows a linear increase in $\bar{\Omega}_w$ and a uniform distribution in Ω_v. This implies convective transfer from Ω_v to $\bar{\Omega}_w$ as in some conceptual models(Grant et al., 1982). However, the time scale for such balance to take place will be comparable to the diffusion time. It is thus ignored in the present case of a moving interface. It then follows that

$$\rho_w h_w\left(u_w - \phi\frac{dr}{dt}\right) = \rho_v h_v\left(u_v - \phi\frac{dr}{dt}\right)$$
$$-(1-\phi)(h_{rv} - h_{ri})\rho_r\frac{dr}{dt},$$

where $h_w = C_{pw}T_i$, h_v, $h_{rv} = C_{pr}T_v$ and $h_{ri} = C_{pr}T_i$ are the enthalpies of water, vapor, rock in Ω_v, and rock at Γ, with T_v and T_i being the temperatures of the superheated vapor and the interface Γ, respectively. After invoking the mass flux continuity (4), it becomes(Woods and Fitzgerald, 1993)

$$\frac{1}{F} = 1 + \frac{\phi}{1-\phi}\frac{\rho_w(h_v - C_{pw}T_i)}{\rho_r C_{pr}(T_v - T_i)} \qquad (5)$$

For saturated liquid and vapor, the temperature is related to the pressure by the Clausius-Clapeyron relation (Look and Sauer, 1988). The following equation will be used for T_i:

$$T_i = -a\Big/\ln(p_i/b) \qquad (6)$$

where $a = 4.71 \times 10^{3\circ}K$ and $b = 3.23 \times 10^4 MPa$ for T_i in the range 373 - 746 $^\circ K$ (Tabor, 1969; Delaney, 1984). As will be shown later, the variation of T_i on descending Γ is significant. In this paper, unlike in Fitzgerald and Woods(1995b) who assumed that $h_v - C_{pw}T_i$ is constant, h_v is determined from thermodynamic tables by using the pressure and temperature of the vapor. T_i is determined by (6) for the vapor pressure.

Scale Estimates

The pressure change P is $O(\rho_w g\bar{r})$ caused by water invasion across Ω_v. From Darcy's law the seepage velocity in $\bar{\Omega}_w$ and $\tilde{\Omega}_w$ is $U_w = O(k/\mu_w(P/D))$. Assuming that the three terms in (1) are comparable, we estimate the time scale of interface movement as $T_r = O(\phi D^2\mu_w/(kP))$. The time scale for pressure diffusion in the vapor zone can be estimated from the equation of mass conservation (Carman, 1956) as $T_{pv} = O(\phi D^2\mu_v/(kP)) = (\mu_v/\mu_w)T_r \ll T_r$. Thus the pressure distibution in Ω_v will be assumed to be uniform. The consolidation time in the liquid zone is given by $T_{cw} = \mu_w D^2/k\mathcal{D}$ where $\mathcal{D}$ is the elastic modulus of the medium. It is thus related to T_r by $T_{cw}/T_r = P/(\mathcal{D}\phi)$ and is very small for typical vaues of $P = O(10^6 Pa)$ and $\mathcal{D} = O(10^{10}Pa)$. Hence, the consolidation equation in the liquid zone is of steady form without local terms(Lee and Mei, 1996). The consolidation time in the vapor zone is much less than T_{cw}.

From (1) the heat convection time in the liquid zone is estimated as $T_{vw} = O(D/U_w) = O(T_r/\phi)$ which is large since $\phi \le 0.1$. The heat diffusion time $T_{dw} = D^2/\alpha_f$, where α_f is the thermal diffusivity of water, is much larger than T_{vw} because $T_{vw}/T_{dw} = \alpha_f/U_w D = \mu_w\alpha_f/kP < O(10^{-3})$. This implies that thermal changes due either to convection or to diffusion in $\bar{\Omega}_w$ and $\tilde{\Omega}_w$ over T_r are small and can be ignored. The medium temperature at any location in $\tilde{\Omega}_w$ is approximately time-independent and is determined by the Clausius-Clapeyron relation when the descending interface Γ passes that location.

The scale of vertical deformation W is estimated from Hooke's law as $O(PD/\mathcal{D})$, which is typically of the order of $10cm$. Obviously, T_r determines the life span of a vapor-dominated geothermal reservoir with natural recharge and is chosen as the reference time scale.

Normalized Equations

Based on the scale estimates, the variables are normalized as follows:

$$
\begin{aligned}
&z = Dz^*, \quad t = T_r t^*, \quad \tilde{p} = P\tilde{p}^* \\
&u_w = U_w u_w^*, \\
&w = Ww^*, \quad T^*(T_v - \overline{T}_i) + \overline{T}_i = T
\end{aligned} \tag{7}
$$

where the symbols with an asterisk are dimensionless and $\overline{T}_i$ is the initial interface temperature.

The governing conditions are summarized in dimensionless variables. We impose that the deviations of the pore pressure, temperature, and solid stress on the watertable at $z^* = 1$ are zero.

The consolidation equation in $\bar{\Omega}_w$ and $\tilde{\Omega}_w$ with negligible effects of solid deformation becomes

$$
\frac{\partial u_w^*}{\partial z^*} = -\frac{\partial^2 \tilde{p}^*}{\partial z^{*2}} = 0 \quad z \in \bar{\Omega}_w + \tilde{\Omega}_w. \tag{8}
$$

The total pressure p^{T^*} is equal to $\bar{p}^* + \tilde{p}^*$ in $\bar{\Omega}_w$ and $\bar{p}^* + p_{wi}^* + \tilde{p}^*$ in $\tilde{\Omega}_w$ where $p_{wi}^* = (\bar{r}^* - r^*(t^*))/\bar{r}^*$ is the liquid pressure due to water invasion. With the boundary conditions (4) and $\tilde{p}^*|_{z^*=1} = 0$, (8) gives

$$
\tilde{p}^*|_{r^*(t^*)} = \frac{1}{1-F}\frac{dr^*}{dt^*}\left[1 - r^*\right]. \tag{9}
$$

Combining (4) and (5) the equation describing $r^*(t^*)$ is given by

$$
-\mathcal{A} = \left[\frac{\rho_r}{\rho_w}\frac{1-\phi}{\phi}\frac{1 - T_i^*}{\frac{h_v - C_{pw}\bar{T}_i}{C_{pr}(T_v - \bar{T}_i)} - \frac{C_{pw}}{C_{pr}}T_i^*} + \frac{\rho_v}{\rho_w}\right]\frac{dr^*}{dt^*} \tag{10}
$$

where $\mathcal{A} = M/(\rho_w U_w)$ is the normalized extraction rate of vapor, M being the steam mass production rate per unit area, and $\rho_w U_w$ is the water seepage rate. For Larderello and the Geysers the production rates are between 0.2 and 0.5(Lipman et al., 1978; Narasimhan and Goyal, 1984). The density ratio ρ_v/ρ_w, which is usually small, is given by the equation of state as

$$
\frac{\rho_v}{\rho_w} = \frac{\bar{\rho}_v}{\rho_w}\left[\frac{p_a}{\bar{P}} + \frac{1 - r^*}{1 - \bar{r}^*} + \frac{P}{\bar{P}}\tilde{p}^*|_{r^*(t^*)}\right] \tag{11}
$$

where p_a and $\bar{P} = \rho_w g(D - \bar{r})$ are the atmospheric pressure and the initial vapor pressure. The Clausius-Clapeyron relation (6) becomes

$$
(T_v - \bar{T}_i)T_i^* = -\bar{T}_i - b\Big/\ln\left[\frac{\bar{P}}{a}\left(\frac{1 - r^*}{1 - \bar{r}^*} + \frac{P}{\bar{P}}\tilde{p}^*|_{r^*}\right)\right] \tag{12}
$$

The reservoir deformation is governed by the equilibrium equation(Lee and Mei, 1995a). The stress deviation from the initial state σ^* is governed by

$$
\frac{\partial \sigma^*}{\partial z^*} = \frac{\partial}{\partial z^*}\left(\frac{\partial w^*}{\partial z^*} - \alpha\tilde{p}^* + C\right) = B \tag{13}
$$

where Hooke's law has been used and the stress component C and the body force B are zero in $\bar{\Omega}_w$ and Ω_v and are given in $\tilde{\Omega}_w$ as

$$
\begin{aligned}
&C(z^*) = -\alpha\frac{\bar{r}^* - z^*}{\bar{r}^*} - \frac{\beta_t(T_v - \bar{T}_i)}{P}(T^* - 1) \\
&B = \phi/\bar{r}^*
\end{aligned} \tag{14}
$$

due to water invasion and thermal cooling from T_v to T_i as the interface descends. Since the time scale T_r is much smaller than the heat convection and diffusion times, $T^*(r^*)$ is given by $T_i^*(r^*)$(cf. (12)).

The following conditions are additionally imposed:

$$
\sigma^*(z^* = 1) = 0, \quad w^*(z^* = 0) = 0 \tag{15}
$$

Integrating (13) across the reservoir depth and invoking the stress and displacement continuities at $z^* = r^*$ and $z^* = \bar{r}^*$, we obtain the vertical subsidence

$$
\begin{aligned}
&w^*|_{r^*} = \int_0^{r^*} \alpha\tilde{p}^* dz^* - \phi\frac{\bar{r}^* - r^*}{\bar{r}^*}r^* \\
&w^*|_{\bar{r}^*} - w^*|_{r^*} = \int_{r^*}^{\bar{r}^*} \alpha\left(\tilde{p}^* + \frac{\bar{r}^* - z^*}{\bar{r}^*}\right)dz^* \\
&+ \int_{r^*}^{\bar{r}^*}\left[\frac{\beta_t(T_v - \bar{T}_i)}{P}(T^* - 1) - \phi\frac{\bar{r}^* - z^*}{\bar{r}^*}\right]dz^* \\
&w^*|_{z^*=1} - w^*|_{\bar{r}^*} = \alpha\int_{\bar{r}^*}^1 \frac{1 - z^*}{1 - r^*}\tilde{p}^*|_{r^*}dz^*
\end{aligned} \tag{16}
$$

Note that the deformation in Ω_v is caused by the pressure change and the weight change in the overlying layer $\tilde{\Omega}_w$ (due to water invasion). In $\tilde{\Omega}_w$, pressures $\tilde{p}^*$ and p_{wi}^*, thermal shrinking and increase of body force contribue(cf.(13) and (14)). In $\bar{\Omega}_w$, only the flow-induced pressure $\tilde{p}^*$ is responsible for deformation. After (9) to (12) are solved for r^*, $\tilde{p}^*|_{r^*}$, ρ_v/ρ_w and $T_i^*(r^*)$ by an iterative scheme, the reservoir deformation is determined from (16).

APPLICATIONS

One-dimensional thermal consolidation is applied to the extraction of vapor from a geothermal reservoir with natural recharge. The fluid and reservoir properties are summarized in Table 1.

Description	Value
total reservoir thickness(D)	$500m$
initial thickness of vapor zone($\bar{r}$)	$400m$
porosity(ϕ)	0.1, 0.02
permeability(k)	$1mD = 10^{-15}m^2$
elastic modulus of rock($\mathcal{D}$)	$10^{10}Pa$
density of rock(ρ_r)	$2600\ kg/m^3$
density of water(ρ_w)	$1000\ kg/m^3$
initial vapor density at $\Gamma(\bar{\rho}_v)$	$5.3\ kg/m^3$
specific heat of rock(C_{pr})	$850\ J/kg^oK$
specific heat of water(C_{pw})	$4200\ J/kg^o$
viscosity of water(μ_w)	$1.3\times10^{-4}kg/ms$
viscosity of vapor(μ_v)	$1.6\times10^{-5}kg/ms$
vapor temperature(T_v)	$300°C$, $250°C$
initial interface temperature($\bar{T}_i$)	$176°C$
initial reservoir pressure($\bar{p}$)	$10^6 Pa$
pressure coefficient(α)	0.6
pressure variation scale(P)	$4\times10^6 Pa$
production rate ratio($\mathcal{A}$)	0.2, 0.4, 0.6
thermal stress ratio($\frac{\beta_t(T_v-\bar{T}_i)}{P}$)	$1.0(T_v = 300°C)$
	$0.60\ (T_v = 250°C)$
enthalpy ratio($\frac{h_v - C_{pw}\bar{T}_i}{C_{pr}(T_v-\bar{T}_i)}$)	$21.9\ (T_v = 300°C)$
	$35.0\ (T_v = 250°C)$

Table 1. Physical Parameters.

In order to examine the effects of different porosity and vapor production rate, ϕ=0.1 and ϕ=0.02 have been chosen for which $\mathcal{A}$=0.2, 0.4 and 0.6 are considered. The initial temperature of the interface $\bar{T}_i$ is calculated from (6) as $176°C$ for $\bar{p} = 10^6 Pa$. Two vapor temperatures are considered, $T_v = 250°C$ and $300°C$. For superheated steam, the enthalpy h_v is obtained from thermodynamic tables for steam (e.g., Haywood, 1990). If the Rayleigh number defined by $Ra = kg\beta_T\Theta L/\nu\alpha_m$ is larger than the critical value of 40, natural convection of the liquid may occur(Nield and Bejan, 1992) where β_T, Θ and α_m are the thermal expansion coefficient of water, temperature difference across the liquid layer of thickness L, and thermal diffusivity of the water-saturated medium. By using $\beta_T = O(10^{-4}{}^oC^{-1})$, $\Theta = \bar{T}_i = 176°C$, $L = 500m$, $\alpha_m = O(10^{-7}m^2/s)$, and the values in Table 1, Ra is estimated as $O(1)$. Therefore the liquid zone is stable throughout the reservoir life.

Porosity $\phi = 0.1$. This corresponds to a typical sedimentary rock reservoir. For $T_v = 300°C$, the time variations of $r(t)$ and F at the interface are shown in Fig. 2(a). The flow-induced pressure $\tilde{p}|_r$ and the total pressure $p^T|_r$ at Γ are shown in Fig. 2(b). As $\mathcal{A}$ increases, the time for Γ to descend from $\bar{r}$ to the bottom obviously decreases(e.g., 87, 52 and 43 years for $\mathcal{A}$=0.2, 0.4 and 0.6). For larger $\mathcal{A}$ the overall F is larger, too, and this slows down the descending movement of Γ. For example, when $r = 200m$, t=50, 28 and 22 years and $\tilde{p}|_r$=-1, -1.8 and -2.3MPa, implying that the temperature at $r = 200m$ decreases with $\mathcal{A}$(cf.(12)) because the initial pressure $\bar{p}$ and the pressure due to water invasion p_{wi} are the same. The total pressure, which includes $\tilde{p}$ and p_{wi}, shows $p^T|_{r=200m}$=2, 1.1 and 0.6MPa. The values of $T_i(r = 200m)$ are calculated as 212, 183 and 147°C for $\mathcal{A}$=0.2, 0.4 and 0.6 when t is 50, 28 and 22 years. Therefore, more liquid vaporizes as it descends for higher $\mathcal{A}$. Fig. 2(a) shows $F(r = 200m)$=0.45, 0.5 and 0.57 for $\mathcal{A}$=0.2, 0.4 and 0.6. This is seen over the entire range: $0 < r(t) < \bar{r}$ in Fig. 2(a). In Fig. 2(c), the total subsidence in the reservoir is shown. The amount increases as -11, -17 and -23cm for $\mathcal{A}$=0.2, 0.4 and 0.6.

As mentioned earlier, the reservoir deformation is caused by the pressure changes $\tilde{p}$ and p_{wi}(denoted with α in (16)), the body force increase due to water invasion, and the thermal compaction. Among these, the thermal compaction is the most dominant component and increases with $\mathcal{A}$ because, as $T_i(r(t))$ decreases with $\mathcal{A}$, the temperature drop (T_v-$T_i(r(t))$) increases and thus thermal compaction increases. The pressure change may generally cause swelling for moderate production rate. However, when the production rate increases, the pressure change itself can turn out to be compaction, if $\tilde{p}$ in Fig. 2(b) exceeds p_{wi} due to water invasion. At the same time, the lower pressure with larger $\mathcal{A}$ causes lower $T_i(r(t))$ and larger thermal compaction. All together the subsidence increases with the production rate.

If $\tilde{p}$ is ignored, as in Fitzgerald and Woods (1995b), the results are very different. First, the responses follow an identical pattern except the difference in the reservoir life, since the production rate $\mathcal{A}$ is directly proportional to the descent velocity dr^*/dt^*(cf.(10)). The pressure at Γ and T_i are overestimated, which results in an underestimated F because the degree of superheating is reduced. Therefore, the descending velocity of Γ is overestimated and the reservoir life is underestimated. We have calculated the present case with $\tilde{p}$ ignored and the result shows that Γ touches the bottom after 70, 35 and 23 years for $\mathcal{A}$=0.2, 0.4 and 0.6, which is precisely inversely proportional to $\mathcal{A}$. The total pressure $p^T|_r$ becomes $5MPa$ uniformly, which corresponds to the hydrostatic pressure for thickness $500m$. There is no difference in the reservoir response for different $\mathcal{A}$. We also note that $T_i(r(t))$ variation over depth $\bar{r}$ is 60, 50 and 40°C for $\mathcal{A}$=0.2, 0.4 and 0.6 and is significant. When this is ignored, $h_v - C_{pw}T_i$ is overestimated and leads to underestimated F(cf.(5)) and overestimated dr^*/dt^*. The reservoir subsidence with $\tilde{p}$ ignored reached uniformly -7.5cm with no regard to $\mathcal{A}$, since the temperature drop is identical for all of the production rates.

Porosity $\phi = 0.02$. This corresponds to reservoirs in igneous(e.g., granite) or metamorphic rocks where the porosity is primarily due to fractures. The results for the case of $T_v = 300°C$ are shown in Figs. 3(a)-(c). As compared to the case with $\phi = 0.1$(Fig. 2(a)), the reservoir life is slightly reduced but F is increased by 60% or more. This implies physically that the descending water is exposed to a much larger volume of rock with temperature T_v and thus vaporization is much more enhanced. Greater vaporization results in smaller magnitude of $\tilde{p}|_r$, i.e. larger $p^T|_r$ as seen from Figs. 3(b) and 2(b). This is due to the increase in F. The density ratio of the vapor to the liquid is intially 1/200 and increases somewhat with time. For larger F the amount of newly produced vapor is substantial due to large density contrast. To balance the pressure drop in Ω_v, the magnitude of $\tilde{p}$ in $\tilde{\Omega}_w$ should increase and thus $p^T|_r$ increases. Accordingly, $T_i(r(t))$ becomes larger than the case with $\phi = 0.1$. The reservoir compaction is smaller than the case with $\phi = 0.1$ because of increased $T_i(r(t))$ e.g., the magnitude of temperature drop (T_v-$T_i(r(t))$) is reduced. The overall reservoir subsidence is reduced to -8, -11 and -14cm for $\mathcal{A}$=0.2, 0.4 and 0.6 as compared with -11, -17 and -23cm in the case of $\phi = 0.1$.

The results for the case with $T_v = 250°C$ are shown in Figs 4(a)-(c). The differences from $T_v = 300°C$ case are similar to the case with $\phi = 0.1$. Due to a lower degree of superheating in Ω_v, the reservoir life and F are reduced. Because of reduced F, $\tilde{p}|_r$ attains greater magnitude, which results in lower $T_i(r(t))$, but not as large as the difference in T_v. As a result, the reservoir compaction in Fig. 4(c) is smaller than that in Fig. 3(c); it is only -3, -6 and -9cm for $\mathcal{A}$=0.2, 0.4 and 0.6.

Effects of Permeability Variation. As shown in the scale estimates, the permeability affects only the interface movement time scale T_r and the seepage velocity. Therefore, when k is increased(or decreased), the discussions so far are valid except that the transient processes take place at a faster(or slower) time proportional to the change in k.

CONCLUSIONS

The one-dimensional thermal consolidation in a vapor-dominated geothermal reservoir, with a recharge that maintains a constant watertable, is analyzed. We showed that the induced pressure is not necessarily small and causes a considerable deviation from the hydrostatic value. In addition, the most dominant mechanism of land subsidence is thermal contraction in the water-invaded region.

As the production rate increases for constant vapor temperature, the descending velocity of the interface, the vaporizing fraction, and the magnitude of flow-induced pressure drop increase. Accordingly, the interface temperature decreases and the thermal compaction in the water-invaded zone increases. This results in an increased land subsidence. For a lower vapor temperature, the reservoir life and vaporizing fraction decrease, but the production-induced pressure drop increases to compensate for the reduced vaporizing fraction. The subsidence also decreases due to less degree of superheating in the vapor zone.

When the porosity decreases, the vaporizing fraction increases substantially due to the greater rock volume at vapor temperature available for vaporization. Due to a greater vaporizing fraction, the flow-induced pressure drop decreases and the interface temperature increases, which leads to reduced subsidence. When the medium permeability is changed, the processes occur in the manner inversely proportional to the permeability change.

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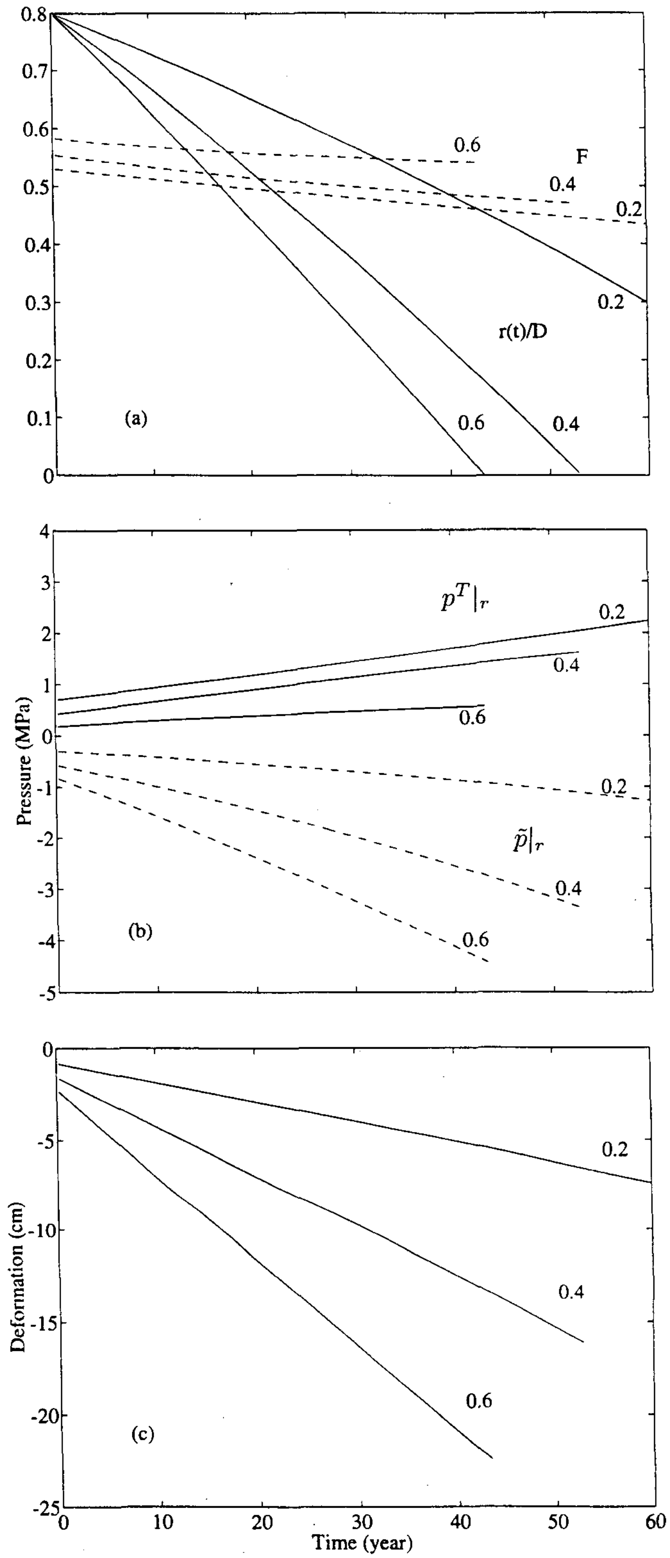

Fig. 2(a)-(c). Time variations of (a) the vaporizing fraction F and the interface location $r(t)/D$, (b) the flow-induced pressure $\tilde{p}|_r$ and the total pressure $p^T|_r$ at the interface, and (c) total subsidence $w(z = D)$ for the case with $\phi = 0.1$ and $T_v = 300°C$. The numbers by each curve denote the production rate $\mathcal{A}$.

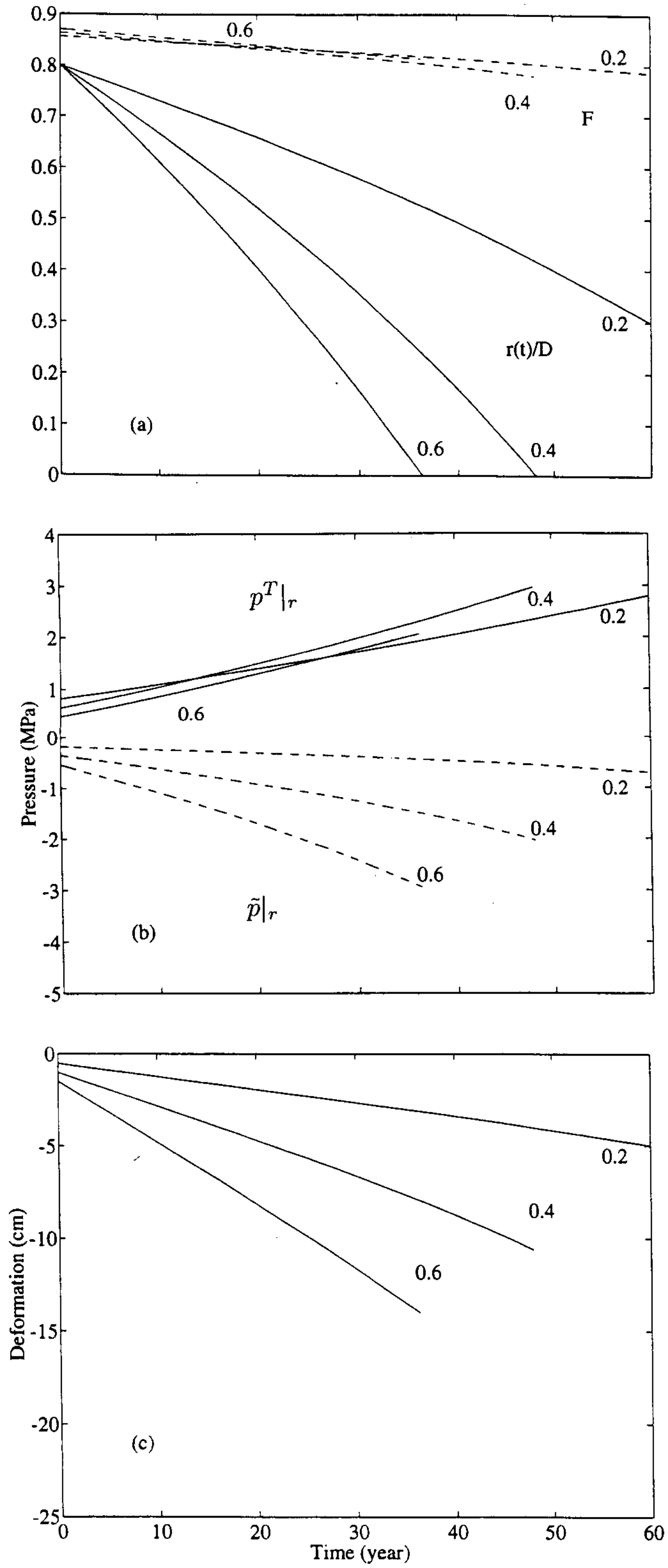

Fig. 3(a)-(c). Time variations of (a) F and $r(t)/D$, (b) $\tilde{p}|_r$ and $p^T|_r$, and (c) $w(z = D)$ for the case with $\phi = 0.02$ and $T_v = 300°C$. See the caption of Fig.2.

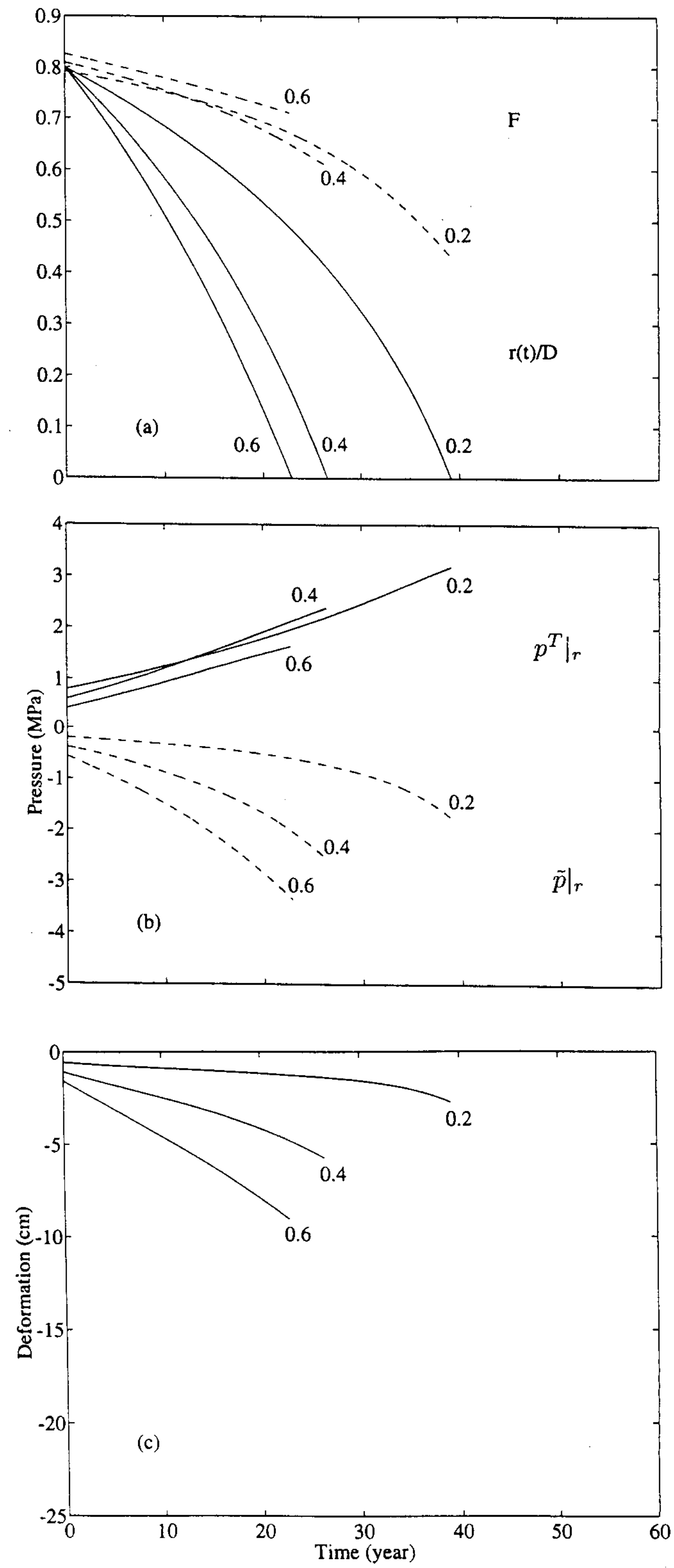

Fig. 4(a)-(c). Time variations of (a) F and $r(t)/D$, (b) $\tilde{p}|_r$ and $p^T|_r$, and (c) $w(z = D)$ for the case with $\phi = 0.02$ and $T_v = 250°C$. See the caption of Fig.2.