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NATURAL VERTICAL FLOW IN THE LOS AZUFRES, MEXICO, GEOTHERMAL RESERVOIR

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ABSTRACT

This work focuses on estimating the mass (M) and energy (E) flow rates, the permeability k, and the relative permeability functions R_L and R_V associated with the natural vertical flow in the reservoir. To estimate M and E we used the standard 1-D vertical equations for two-phase flow, complemented with boundary conditions at the boiling and dew interfaces. These boundary conditions were derived in an earlier stage of this study that established an approximate 1-D vertical model of the reservoir. The estimated values of M and E were then used together with the previously established liquid saturation vertical profile of the reservoir, and the differential equation expresing the pressure gradient, to fit, by trial and error, the observed natural pressure profile. The accuracy of the fit depends on the assumed value for the vertical permeability and on the chosen forms for the relative permeability functions. We estimated M ~ 6.9×10^{-8} kg m^{-2} s^{-1} and E ~ 0.2 W m^{-2}. These results lie well within the ample ranges of mass and energy flowrates per unit area found in geothermal fields worldwide. The estimated values of M and E support the previous inference that there is an extensive caprock in the reservoir. Our best fit to the natural pressure gradient implies a vertical permeability of about 0.08 mD, residual water- and steam-saturations of about 0.04 and 0.00 respectively, and "fracture relative permeabilities" (i.e., $R_L+R_V=1$). This work addresses a major obstacle for a succsesfull analysis of the Los Azufres geothermal reservoir, which is characterized by an extensive two-phase region: the former unavailability of reasonably reliable relative permeability functions. Furthermore, the present characterization of the vertical natural flow provides important constraints for both lumped- and distributed-parameter models of the reservoir. Finally, this work gives information on reservoir properties that would be difficult to obtain by other means.

INTRODUCTION

Geothermal reservoir assesment generally requires a conceptual model, a quantitative mathemathical model based on the former, initial conditions, and boundary conditions. For Los Azufres we recently developed a quantitative-conceptual 1-D vertical model (Iglesias et al., 1985a, 1985b, 1985c). However, in order to charactherize the initial conditions for the model, we needed information about the natural mass and energy output of the field, for which no direct measurements exist. Furthermore, for the mathematical model we lacked reasonably reliable relative permeability functions, and knowledge about the magnitude of the vertical permeability.

In this paper we estimate the mass and energy flowrates per unit area, the permeability, and the relative permeability functions associated with the natural vertical flow in Los Azufres. The basic equations and some of the ideas on which the present work is based were presented by Pritchett (1979). This author discussed 1-D vertical two-phase flow and heat transfer in high-temperature hydrothermal systems. In particular, Pritchett stressed the possibility of obtaining insight on the relative permeabilities from comparison of synthetic vertical profiles of pressure, temperature, saturation and the like, whose forms depend on the details of the chosen relative permeability functions, with downhole measurements.

Our estimates are also based on data concerning the conditions at the boiling and dew elevations of the system, and on the natural vertical saturation and pressure profiles taken from our previous conceptual-quantitative 1-D vertical model of the Los Azufres reservoir (Iglesias et al., 1985a, 1985b, 1985c). Figure 1 summarises this model. The model reveals the existence of a "stack" composed of a deep compressed-liquid zone, a two-phase liquid-dominated zone, a two-phase vapor-dominated zone, and a dry-steam zone (this last zone in the fractures and cracks that vent the steam to the surface). Another important feature of the model is that the pressures of the natural reservoir were approximately fitted by a composite boiling-point-for-depth/vaporstatic pressure profile. Figure 2 ilustrates the liquid saturation vertical profile obtained from this model.

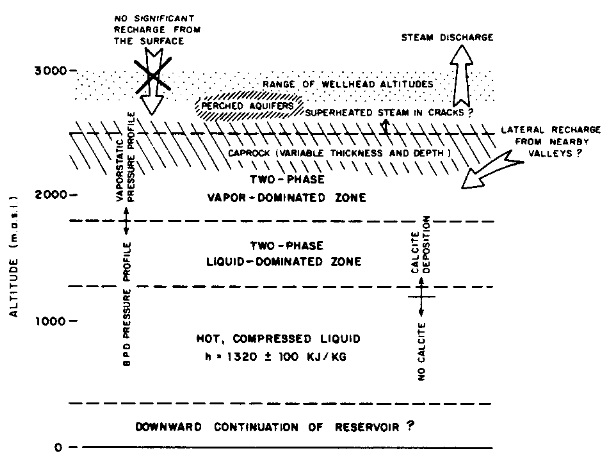

Fig. 1 A schematic 1-D vertical, conceptual model of the reservoir (after Iglesias et al., 1985c).

<u>METHOD</u>

Pritchett (1979) combined the equations describing the conservation of mass, momentum, and energy for vertical two-phase flow in porous media, in two compact equations: the pressure gradient law,

$$\frac{dP}{dz} = -g\left(\frac{R_V\, \rho_V^2\, \mu_L + R_L\, \rho_L^2\, \mu_V + M\, \frac{\mu_L\, \mu_V}{k\, g}}{R_V\, \rho_V\, \mu_L + R_L\, \rho_L\, \mu_V}\right) \tag{1}$$

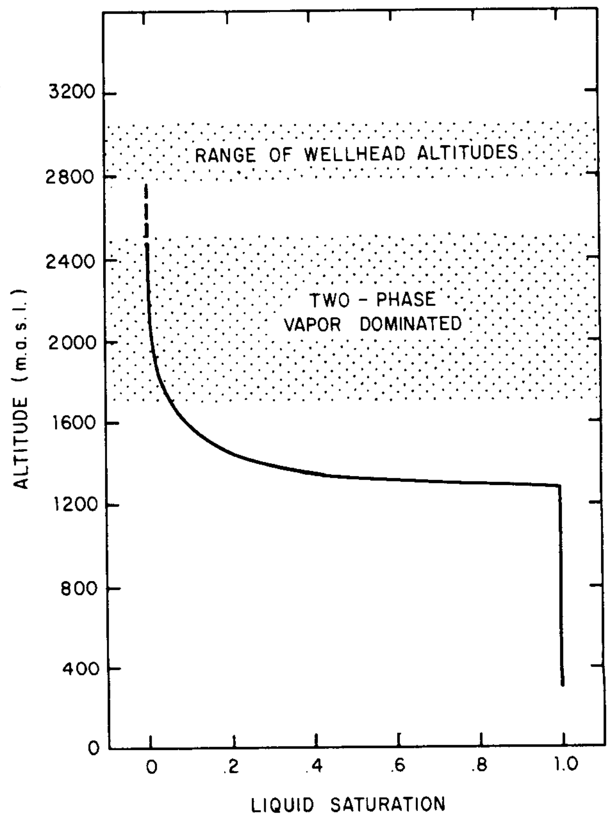

Fig. 2 The vertical profile of the liquid saturation in the model (after Iglesias et al., 1985c).

and the constitutive constraints equation,

$$R_V\left[\left(\frac{E}{k\, g}\right)\left(\frac{\mu_L}{\rho_L^2\, h_V}\right) - \left(\frac{M}{k\, g}\right)\left(\frac{\mu_L}{\rho_L^2}\right) - \left(\frac{K}{k}\right)\left(\frac{\gamma\, \rho_V\, \mu_L}{\rho_L^2\, h_V}\right)\right] + R_L\left[\left(\frac{E}{k\, g}\right)\left(\frac{\mu_V}{\rho_L\, \rho_V\, h_V}\right) - \left(\frac{M}{k\, g}\right)\left(\frac{\mu_V\, h_L}{\rho_L\, \rho_V\, h_V}\right) - \left(\frac{K}{k}\right)\left(\frac{\gamma\, \mu_V}{\rho_V\, h_V}\right)\right]$$

$$-R_L\, R_V\left(1 - \frac{\rho_V}{\rho_L}\right)\left(1 - \frac{h_L}{h_V}\right) = \left(\frac{M}{k\, g}\right)\left(\frac{K}{k}\right)\left(\frac{\mu_L}{\rho_L^2}\right)\left(\frac{\gamma\, \mu_V}{\rho_V\, h_V}\right) \tag{2}$$

(notation at the end of the paper).

In the compressed-liquid region S = 1, R_L = 1 and R_V = 0, and the pressure gradient is given by

$$\frac{dP}{dz} = -\left(g\,\rho_L + \frac{M}{k}\frac{\mu_L}{\rho_L}\right) \qquad (3)$$

To estimate M and E, we applyed the boundary conditions

$S = 1,\ R_L = 1\ ,\ R_V = 0$ at $z = z_B$,

$S = 0,\ R_L = 0\ ,\ R_V = 1$ at $z = z_D$,

at the boiling (B) and dew (D) elevations, to (1) and (2). Thus we obtained a system of 4 equations in 4 unknowns: M, E, k_B, and k_D. The corresponding solutions are:

$$M = \frac{K\left[\gamma_B\left(\frac{dP}{dz}\right)_B - \gamma_D\left(\frac{dP}{dz}\right)_D\right]}{(h_{VD} - h_{LB})} \qquad (4)$$

$$E = M\,h_{LB} + K\,\gamma_B\left(\frac{dP}{dz}\right)_B$$

$$= M\,h_{VD} + K\,\gamma_D\left(\frac{dP}{dz}\right)_D \qquad (5)$$

$$k_B = \frac{M}{\frac{\rho_{LB}}{\mu_{LB}}\left[\left(\frac{dP}{dz}\right)_B - g\,\rho_{LB}\right]} \qquad (6)$$

$$k_D = \frac{M}{\frac{\rho_{VD}}{\mu_{VD}}\left[\left(\frac{dP}{dz}\right)_D - g\,\rho_{VD}\right]} \qquad (7)$$

Solutions (4)-(7) assume that the thermal conductivity is a simple constant, independent of altitude. This is frequently a reasonable assumption (e.g., Pritchett, 1979), and there seems to be no reason to invalidate it in Los Azufres.

We were able to use equations (3) and (4) to estimate M and E for Los Azufres. The necessary values of the pressure gradients, enthalpies, and γ's were known from the previous quantitative vertical model (Iglesias et al., 1985a, 1985b, 1985c). However, the permeabilities k_B and k_D could not be estimated by means of (5) and (6) because that requires evaluation of the **differences** ($dP/dz - g\rho_L)_B$, ($dP/dz - g\rho_V)_D$, between the dynamic and the static pressure gradient. Normally these differences are of the order of 10% of the value of the static gradient (e.g., Grant et al., 1982). Unfortunately, the dispersion of the measured pressure profile (fig. 3) precludes reasonably reliable evaluation of said differences in our case. Therefore, we resorted to another approach to obtain information on the vertical permeability.

If estimates of M and E are available, the pressure gradient equations (1) and (3) can be used together with the liquid saturation vertical profile (fig. 2) to fit, by trial and error, the measured pressure profile (fig. 3). The fit depends on the vertical distribution assumed for **k**, and on the forms of the relative permeability functions $R_L(S)$ and $R_V(S)$ chosen for the synthetic profile.

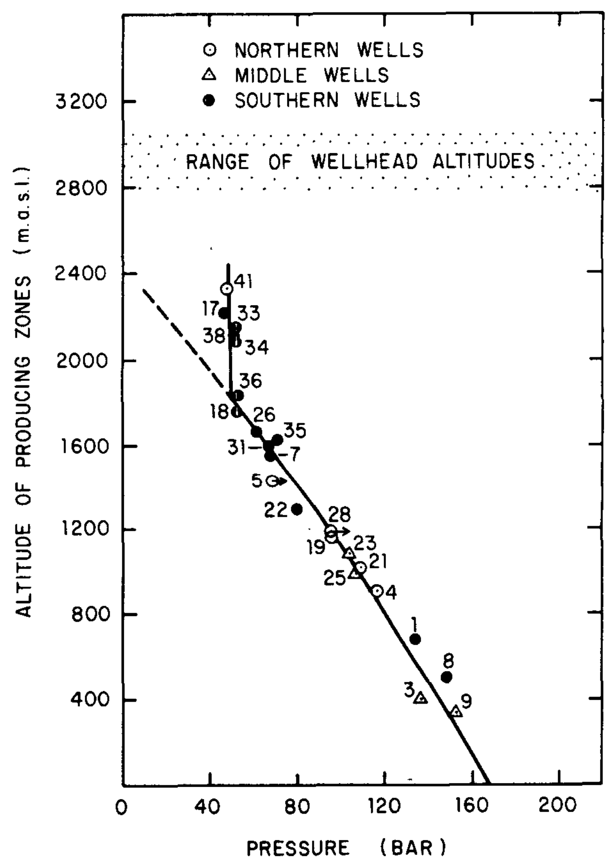

Fig. 3 The measured pressure profile, with the composite BPD-vaporstatic profile (after Iglesias et al., 1985c).

Lacking information about the vertical distribution of **k**, we adopted the simplest assumption: **k** is a constant independent of altitude. Thus, the magnitude of **k** derived from the fitting process must be regarded as an equivalent vertical permeability representative of the areally-lumped 1-D vertical model.

To compute the synthetic pressure profiles, equations (1) and (3) were numerically integrated subjected to the constraints

$$S = S(z); \quad R_L = R_L(S); \quad R_V = R_V(S),$$

and to the boundary conditions

$$P(z_{min}) = Pmax; \quad P(z_D) = P_D,$$

where z_{min} is the elevation corresponding to the maximum pressure of the quantitative-conceptual model. Naturally, the forms of the relative permeability functions must be defined before integration can proceed.

The actual fitting procedure involved manipulation of the fitting parameters (k and the relative permeability functions) and repeated integrations until a satisfactory fit was achieved.

Like other inverse (in the mathematical sense) methods, the method just described does not guarantee the uniqueness of the solution. Fortunately, the observed pressure profile at Los Azufres is particularly difficult to fit due to the existence of a pronounced "knee" at about 1800 m a.s.l., the altitude corresponding to the transition from a water-dominated to a vapor-dominated system (e.g., fig. 3). The greater difficulty hopefully circumscribes the range of fitting parameters that reasonably represent solutions.

RESULTS AND DISCUSSION

Using $K = 1.8$ W m^{-2} in (4) and (5), as suggested by the, so far, only available direct measurements of thermal conductivity for andesites from Los Azufres (Contreras et al., 1986), we estimated

$$M = 6.9\times10^{-8} \text{ kg m}^{-2} \text{ s}^{-1},$$

$$E = 0.2 \text{ W m}^{-2}.$$

The computed mass flux is well within the ample range of mass fluxes found in geothermal fields worldwide. Adopting 30 km^2 as the area of the reservoir (e.g., de la Cruz and Castillo, 1984; Iglesias et al., 1985b, 1985c), the value inferred for M implies a natural discharge for Los Azufres of about 50 ton/hr of steam [no geothermal liquid is discharged in the field (Rodriguez et al., 1984; Iglesias et al., 1985c)]. This small natural discharge is compatible with the field discharging exclusively steam and with the fact that the discharge area is small with respect to the reservoir area. As is well known, the natural discharges in Los Azufres are far from reaching the intensity and spectacularity observed in other geothermal fields. This result reinforces the available evidence indicating the existence of an extensive caprock in the reservoir. If the system is in steady state, as indicated by some evidence (Iglesias et al., 1985b, 1985c), this result also indicates the magnitude of the **natural** recharge.

The value inferred for the natural thermal flow is significantly greater than the normal average thermal flow. The average heat flow in thermally "normal" continental regions is 0.05-0.06 W m^{-2} (e.g., Goguel, 1976; Elder, 1976; Jessop et al., 1976). Thus, the natural thermal flow in Los Azufres is clearly within the range of the thermally anomalous regions, as expected. The relative importances of the conductive and convective componentes of the deep thermal flow in Los Azufres can be assesed by means of equation (5); in this way it is easy to show that the contributions of both components are comparable at the boiling and dew altitudes. Adopting, as before, 30 km^2 as the reservoir area, the value inferred for E implies a natural thermal discharge for Los Azufres of about 6 MW.

Our best-fit estimates of the vertical permeability and relative permeability functions were obtained from the fit ilustrated in fig. 4; compare with the composite BPD-vaporstatic profile of fig. 3. The estimates are

$$k = 0.08\times10^{-15} \text{ m}^2,$$

$$R_L = [(S-S_0)/(1-S_0)]a, \tag{8}$$

$$R_V = 1-R_L, \tag{9}$$

$$S_0 = 0.04, \quad S_{0V} = 0, \tag{10}$$

$$a = 0.2, \tag{11}$$

where S_0 is the liquid irreducible saturation, S_{0V} the vapor irreducible saturation, and **a** a real, positive exponent.

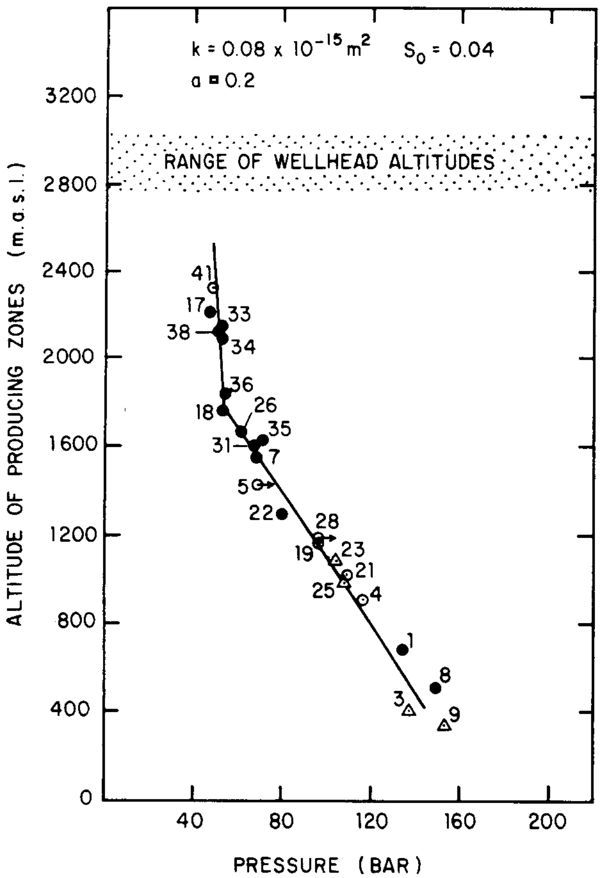

Fig. 4 Best fit to the measured pressure profile.

The successful fit of the observed pressure profile provides circumstantial evidence in favor of the validity of the "fracture relative permeabilities" condition. A non-zero liquid irreducible saturation and a zero vapor irreducible saturation were also necessary for a succsessful fit. The forms of the resulting relative permeability functions are shown in fig. 5.

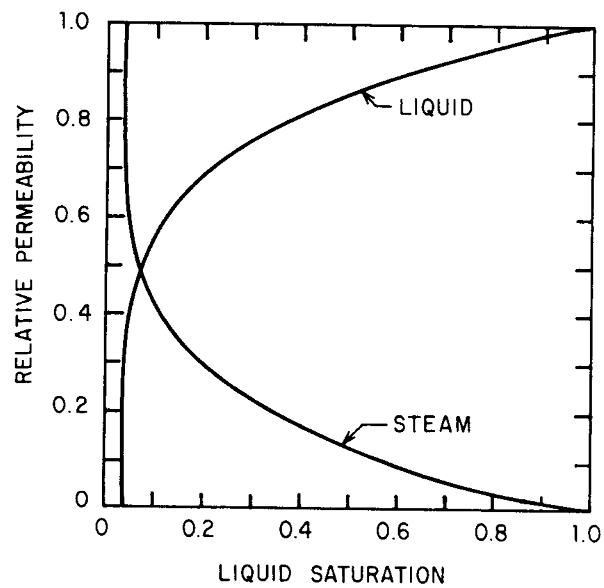

Fig. 5 Derived relative permeability functions.

The inferred vertical permeability is significantly smaller than the horizontal fracture permeabilities deduced from pressure well tests, which span the range 10^{-15} to 30×10^{-15} m^2 (e.g., Iglesias and Arellano, 1985); however, its magnitude is comparable with those of the matrix permeabilities measured in drill cores from Los Azufres, which vary approximately from less than 0.002×10^{-15} to 0.2×10^{-15} (Contreras et al., 1986).

For the relative permeability functions we adopted the so called "fracture relative permeabilities" condition (9) (e.g., Grant et al., 1982). This was done because (a) there is compelling geologic (e.g., Razo, 1984; Garfias, 1984; Huitron, 1985; de la Cruz and Castillo, 1984) and well testing (e.g., Iglesias and Arellano, 1985) evidence that Los Azufres is a naturally fractured reservoir; and (b) we were unable to obtain a satisfactory fit with Corey-type or other multicomponenet-oriented relations.

The sensitivity of the fit to the fitting parameters **k**, S_0 and **a** is illustrated in figs. (6)-(8) respectively. In these figures the continuous line indicates the best fit.

<u>SUMMARY</u>

We have estimated the mass and energy fluxes, the permeability and the relative permeability functions associated with the natural vertical flow in the reservoir. The results for M (~ 6.9×10^{-8} kg m^{-2} s^{-1}) and E (~ 0.2 W m^{-2}) lie well within the ample ranges of mass and energy flowrates per unit area found in geothermal fields worldwide. These results support the previous inference that there is an extensive caprock in the reservoir. Our best fit to the natural pressure gradient implies a vertical permeability of about 0.08 mD, residual water- and steam-saturations of about 0.04 and 0.00 respectively, and "fracture relative permeabilities" (i.e., $R_L+R_V=1$). This work addresses a major obstacle for a succsesfull

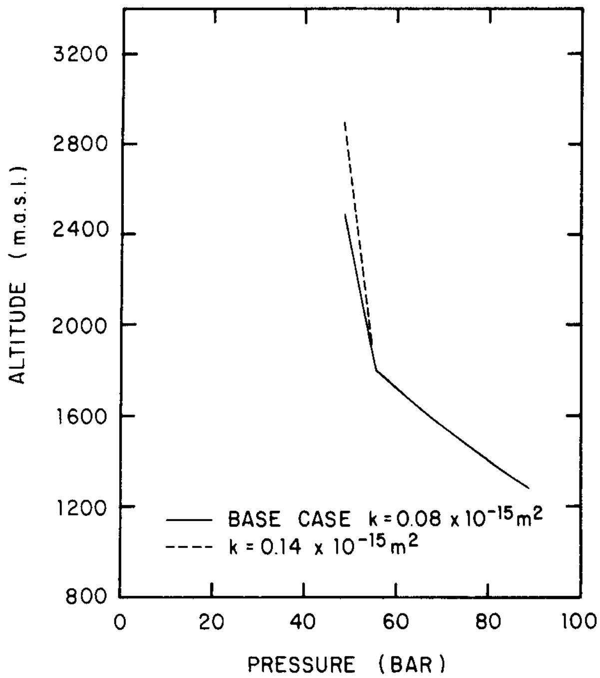

Fig. 6 Sensitivity of the fit to the vertical permeability.

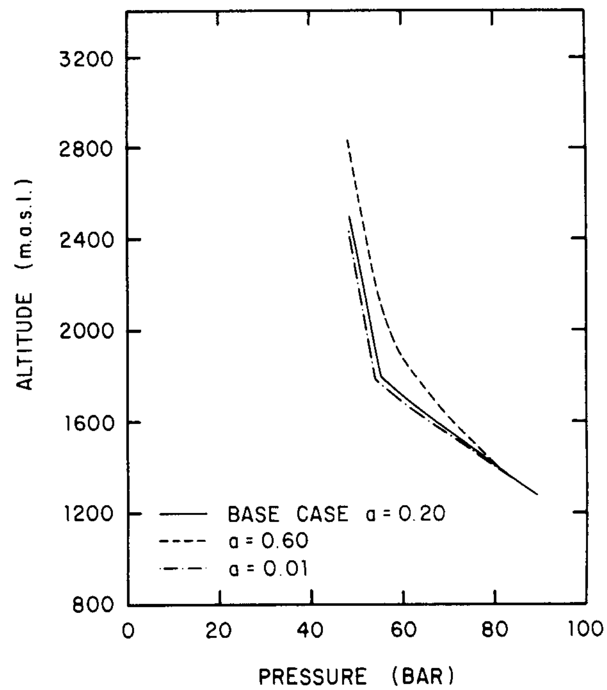

Fig. 8 Sensitivity of the fit to the exponent **a**.

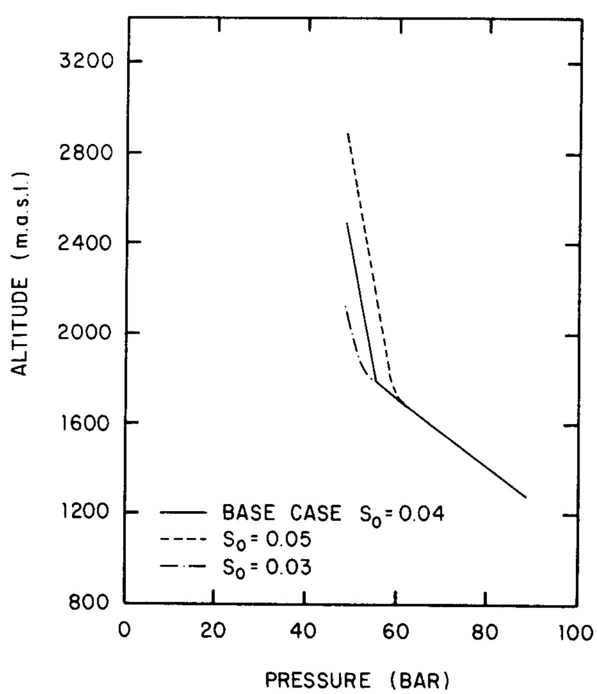

Fig. 7 Sensitivity of the fit to the irreducible liquid saturation.

analysis of the Los Azufres geothermal reservoir, which is characterized by an extensive two-phase region: the former unavailability of reasonably reliable relative permeability functions. Furthermore, the present characterization of the vertical natural flow provides important constraints for both lumped- and distributed-parameter models of the reservoir. Finally, this work gives information on reservoir properties that would be difficult to obtain by other means.

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NOMENCLATURE

E : upward energy flux (W m^{-2})

g : gravity (m s^{-2})

γ : dT/dP (^{o}C Pa^{-1})

h_L : enthalpy of liquid phase (J kg^{-1})

h_V : enthalpy of vapor phase (J kg^{-1})

k : vertical permeability (m^2)

K : vertical thermal conductivity (W m^{-1} C^{-1})

M : upward mass flux (kg m^{-2} s^{-1})

μ_L : liquid-phase viscosity (Pa s)

μ_V : vapor phase viscosity (Pa s)

P : fluid pressure (Pa)

R_L : liquid-phase relative permeability (dimensionless)

R_V : vapor-phase relative permeability (dimensionless)

ρ_L : liquid-phase density (kg m^{-3})

ρ_V : vapor-phase density (kg m^{-3})

S : liquid saturation (dimensionless)

T : temperature (^{o}C)

z : altitude (m a.s.l.)

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