

ROCK THERMAL CONDUCTIVITY AT THE CAP ROCK AND INITIAL CONDITIONS IN TWO-PHASE VOLCANIC HYDROTHERMAL SYSTEMS

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ABSTRACT

Numerical experiments are performed to investigate the rock thermal conductivity influence in the formation of the thermodynamic initial conditions of two-phase systems located in volcanic rocks. These systems exhibit pressure and temperature profiles characterized by a sudden change or discontinuity in their vertical gradients. Vapor dominated, two-phase fluids are found at the upper reservoir's levels. Liquid is the dominated phase within the layers below some critical point.

Numerical results presented in this paper, suggest that the vertical location of this point of discontinuity be controlled by the thermal conductivity existing between the limit of the reservoir and the caprock. Too high values could originate liquid dominated reservoirs. Small values would be at the origin of vapor dominated reservoirs. A characteristic middle value could be responsible for the formation of a counter flow mechanism originating the initial conditions observed at some locations of the Los Azufres, Mexico, geothermal field.

INTRODUCTION

In several volcanic geothermal fields, the temperature difference between top and bottom of the reservoir is remarkable. For example, at Tejamaniles, the southern sector of the Los Azufres, Mexico hydrothermal system, the deepest drilled well (Az-47) has a temperature of 358 °C at the bottom (2964 meters depth); while at the surface the average temperature is about 15 °C. In this sector, the measured thermal conductivity has a mean value of 1.86 W/m/°C (Contreras et al, 1988). Thus the average conductive heat flow is about 0.22 W/m², corresponding to an average thermal gradient of 0.12 °C/m. A value four times the normal geothermal gradient of the Earth's surface (0.03 °C/m). At Los Humeros, Mexico the temperature difference is about 400 °C between the bottom (2847 m depth) and the surface, which corresponds to an average thermal gradient of 0.14 °C/m; with an average measured thermal conductivity of 2 W/m/°C (Contreras et al, 1990). This originates a conductive heat flow of about 0.28 W/m². In this paper, the effect of thermal conductivity on the initial thermodynamic state at the Tejamaniles geothermal subsystem is discussed.

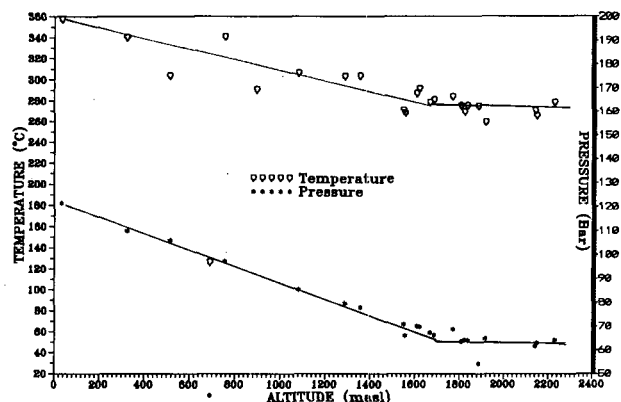
THEMAL CONDUCTIVITY AND INITIAL STATE

The rock thermal conductivity within any geothermal reservoir is a clue parameter to the conductive heat flow, to the distribution of temperatures and to the definition of a barrier to hold the accumulated energy. The thermal conductivity of volcanic rocks depends mainly on the characteristics of its mineral elements, on the conductivity of the fluids filling the pores and on the size and geometry of the pore space (Zimmerman, 1988).

At Los Azufres, the rocks that have been found to form the reservoir's lithology are fractured andesites, rhyolites and some dacites. The andesites forming the reservoir show several degrees of hydrothermal alteration (Viggiano, 1987). An impervious cap rock overlying the reservoir, is formed by rhyolites having zero or very low local permeability associated to small fractures and cracks. A cap rock just obstructs the escape of mass and heat through convection. But the heat loss through conduction is only partially prevented by the rhyolites. Two questions emerge: a) What amount of thermal energy outflows from the reservoir to the atmosphere? b) How this loss influences the natural thermodynamic conditions of the reservoir?

The natural state observed at Los Azufres, showed that vertical pressure and temperature gradients were small between 1700 - 2250 masl, showing nearly vaporstatic conditions. From 0 to 1700 masl the observed gradients correspond to boiling hydrostatic conditions (Fig.1).

Fig. 1.- TEMPERATURE AND PRESSURE PROFILES AT TEJAMANILES



Thereafter the thermodynamic gradients have a discontinuity in the vicinity of 1700 masl. This discontinuity appears also in the vertical distribution of the rock thermal conductivity, having the critical point located around 1800 masl.

Several petrophysical measurements were performed in drilling cores from Los Azufres geothermal field. The reported results involved thermal and mechanical properties belonging to 24 cores of 17 wells (Contreras et al, 1988). The measured properties are: density of dry rock, porosity (total and effective), absolute permeability, rock compressibility, Young and Poisson's modulus, specific heat, thermal diffusivity and thermal conductivity.

Figure 2 shows the vertical distribution of thermal conductivity of cores from wells in the southern sector. Assuming a linear relation between K_T and the altitude Z , the resulting graph suggests that around 1850 masl, the slope of the straight line changes abruptly.

The functional relation $K_T(Z)$ is approximately represented by the following model (R^2 is the correlation coefficient):

$$K_T(Z) = 1.87 - 1.76 \cdot 10^{-4} Z \text{ [W/m/}^\circ\text{C]} \\ \text{if } Z \in [-79, 1850] \text{ masl; } R^2=0.93$$

$$K_T(z) = 7.65 - 2.66 \cdot 10^{-3} Z \text{ [W/m/}^\circ\text{C]} \\ \text{if } Z \in [1850, 2850] \text{ masl; } R^2=1.0$$

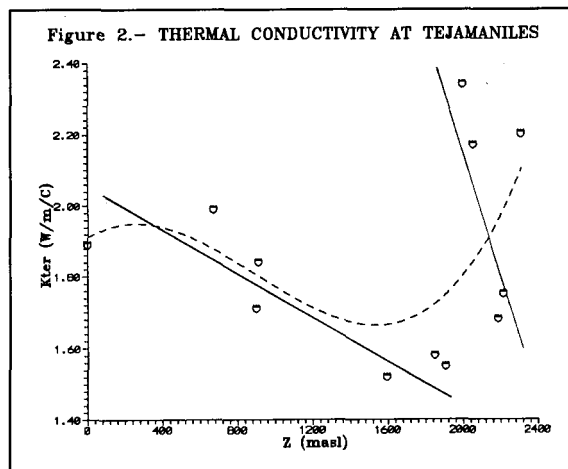
The slope discontinuity is:

$$\{\text{slope}\}_{1850} = 2.66 \cdot 10^{-3} / 1.76 \cdot 10^{-4} = 15.11$$

On the other hand, the vertical thermal gradient is heterogeneous at Tejamaniles, as is illustrated in Table 1. From this table it is implied that in the portions of the reservoir with no evidence of cap rock (wells Az-7 and Az-8), the shallow thermal gradient is 7 to 10 times larger than the normal gradient, suggesting the

Table 1.- SOME THERMAL GRADIENTS MEASURED AT TEJAMANILES.

WELL	dT/dZ (°C/m)	DEPTH (m)	ROCK TYPE
Az-07	0.21	300	Andesites
Az-07	0.31	500	Andesites
Az-08	0.34	400	Andesites
Az-10	0.07	100	Out of the Reservoir
Az-10	0.03	500	"
Az-26	0.06	100	Rhyolites
Az-26	0.11	400	Rhyolites
Az-26	0.54	600	Andesites
Az-26	0.84	700	Andesites
Az-26	0.01	1200	Andesites



existence of an important heat outflowing the reservoir by conduction. The cap rock reduces considerably the thermal gradient at the same depth (well Az-26). Below the rhyolites the thermal gradient increases rapidly until it reaches a zone where the temperature is almost constant. The thermal gradient at well Az-10, outside the reservoir, corresponds to a normal geothermal gradient. These simple facts originate a plausible hypothesis: The caprock obstructs partially the loss of heat by conduction. Possibly the value of its thermal conductivity could greatly affect the formation of the natural thermodynamic conditions of two-phase reservoirs.

NUMERICAL EXPERIMENTS

To understand the thermal conductivity influence on the behavior of this type of system, a number of steady state simulations were performed. The complex real geology was idealized by a vertical section with 10^4 m^2 cross sectional area and a total depth of 3000 m. The geometric model is divided into 15 single-porosity elements (Fig.3). Thirteen elements (Tej N, $N=1,13$) represent the permeable reservoir. Element AQUITARD, with fixed boundary conditions ($T=350^\circ\text{C}$; $P=171 \text{ bar}$), represents the bottom of the andesitic column in contact with an assumed deeper HORNFELS of 500 m total thickness and acting as a continuous heat source. Element Tej01 is overlaid by a caprock of 600 m total thickness, which is connected at the top to a larger element representing atmospheric boundary conditions ($T=15^\circ\text{C}$; $P=0.73 \text{ bar}$).

Other parameters (most obtained from actual field data) for the numerical simulations are given in Table 2. The calculations were performed using the LBL code MULKOM, with a water-carbon dioxide equation of state (Pruess, 1988).

DISCUSSION OF RESULTS

A first simulation started from uniform thermodynamic conditions throughout the system. In response to the temperature difference at the bottom, the system goes through a very long transient evolution, reaching a steady

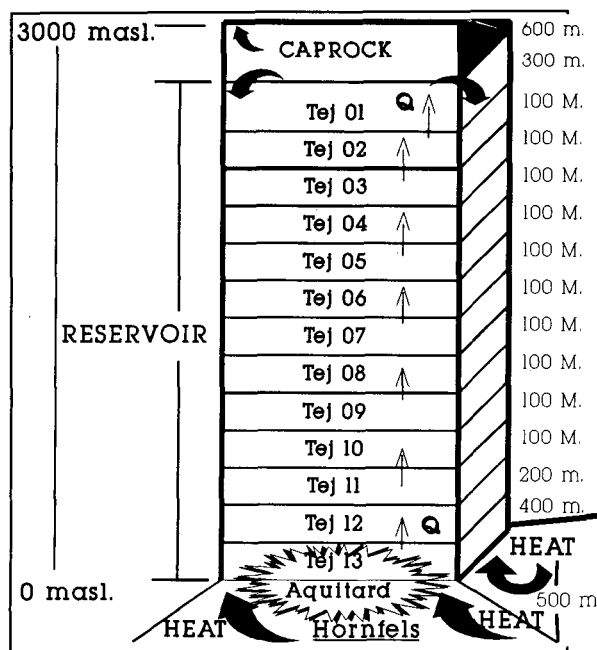


Fig.3- Vertical Geometric Model.

state. The steady state conditions achieved in the first experiment were used as initial conditions for subsequent simulations. Keeping the initial parameters shown in Table 2, several simulations were performed, with different values of K_T at the caprock and with the same boundary conditions. Different steady states were achieved for each value of thermal conductivity at the caprock. Results for ten states are presented in figures 4-7. Figs. 4 and 5 show that a value of $K_T \approx 0.175$ W/m/°C reproduces observed P and T profiles at Tejamaniles. On the other hand, the lowest thermal conductivity value measured in available drill cores is 1.05 W/m/°C. The shorter K_T required, can be interpreted as a simple weighted average of different mineral and fluid components, each having its own thermal conductivity. More complex averages were shown by Zimmerman (1988). Furthermore, results of McKibbin & Pruess (1988), and of Suárez, Pruess & Lippmann (1989), showed that CO₂ tends to accumulate in a condensation zone at the upper limit of the reservoir. A series model can be used to obtain the desired effective average value of K_T :

$$K_T^{-1} = (1-\phi) K_{rock}^{-1} + \phi K_{fluid}^{-1}$$

Assuming a porosity $\phi = 10\%$, $K_{rock} = 1.65$ W/m/°C and $K_{fluid} = 0.02$ W/m/°C (gas).

The corresponding $K_T = 0.18$ W/m/°C (!)

CONCLUSIONS

The numerical simulations described, proved that natural thermodynamic conditions existing in some regions of two-phase systems such as Los Azufres reservoir, are remarkably influenced by the thermal conductivity of the caprock. The breaks in pressure and temperature profiles, the associated sharp drop in vapor saturation and the vertical position of the discontinuity point, are controlled by the thermal conductivity value at the reservoir/caprock interface. High values could give origin to liquid dominated reservoirs. Small values would originate vapor dominated reservoirs at high temperature. A middle effective value could be the cause of the initial conditions at Los Azufres geothermal field.

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Table 2.- PARAMETERS USED IN THE SIMULATIONS

Thickness (m)	Element	Rock Density (kg/m ³)	Porosity (%)	Vertical Permeability (m ²)	Initial Pressure (bar)	Initial Temp. (°C)	Initial Partial P(CO ₂)	Thermal Conductivity (W/m/°C)
-	ATMOS	-	-	1.0 10 ⁻¹²	0.73	15	3. 10 ⁻⁴	0.025
600	CAP01	2251	1.95	1.0 10 ⁻²⁰	55	265	5	K _T
300	TEJ01	2355	11.95	1.0 10 ⁻¹⁴	55	265	5	1.65
100	TEJ02	2434	8.32	1.0 10 ⁻¹⁵	55	265	5	2.19
100	TEJ03	2434	8.32	1.0 10 ⁻¹⁵	55	265	5	2.45
100	TEJ04	2434	8.32	1.0 10 ⁻¹⁵	55	265	5	2.72
100	TEJ05	2434	8.32	1.0 10 ⁻¹⁵	55	265	5	1.56
100	TEJ06	2434	8.32	1.0 10 ⁻¹⁵	55	265	5	1.58
100	TEJ07	2528	5.50	1.0 10 ⁻¹⁵	55	265	5	1.59
100	TEJ08	2528	5.50	1.0 10 ⁻¹⁵	55	265	5	1.61
100	TEJ09	2528	5.50	1.0 10 ⁻¹⁵	55	265	5	1.63
100	TEJ10	2528	5.50	1.0 10 ⁻¹⁵	55	265	5	1.65
100	TEJ11	2677	2.95	1.0 10 ⁻¹⁵	55	265	5	1.66
200	TEJ12	2677	2.95	1.0 10 ⁻¹⁵	55	265	5	1.69
400	TEJ13	2677	2.95	1.0 10 ⁻¹⁵	55	265	5	1.74
500	ACUIT	2834	1.59	1.0 10 ⁻¹⁸	171	350	1	1.82

K _T (W/m/°C)	0.100	0.125	0.150	0.175	0.200	0.225	0.300	0.460	0.600	1.000
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Complementary Parameters

Rock Specific Heat = 1165 J/kg/°C (homogeneous)
Residual Liquid Saturation = 0.30
Residual Vapor Saturation = 0.05 (Corey's Relations)
Diffusive Vapor Flux Coef. = 1.38 10 ⁻⁵ m ² /seg
Initial Steam Saturation = 0.30
Capillary Pressure ----- neglected

Fig.4 - VERTICAL PRESSURE DISTRIBUTIONS

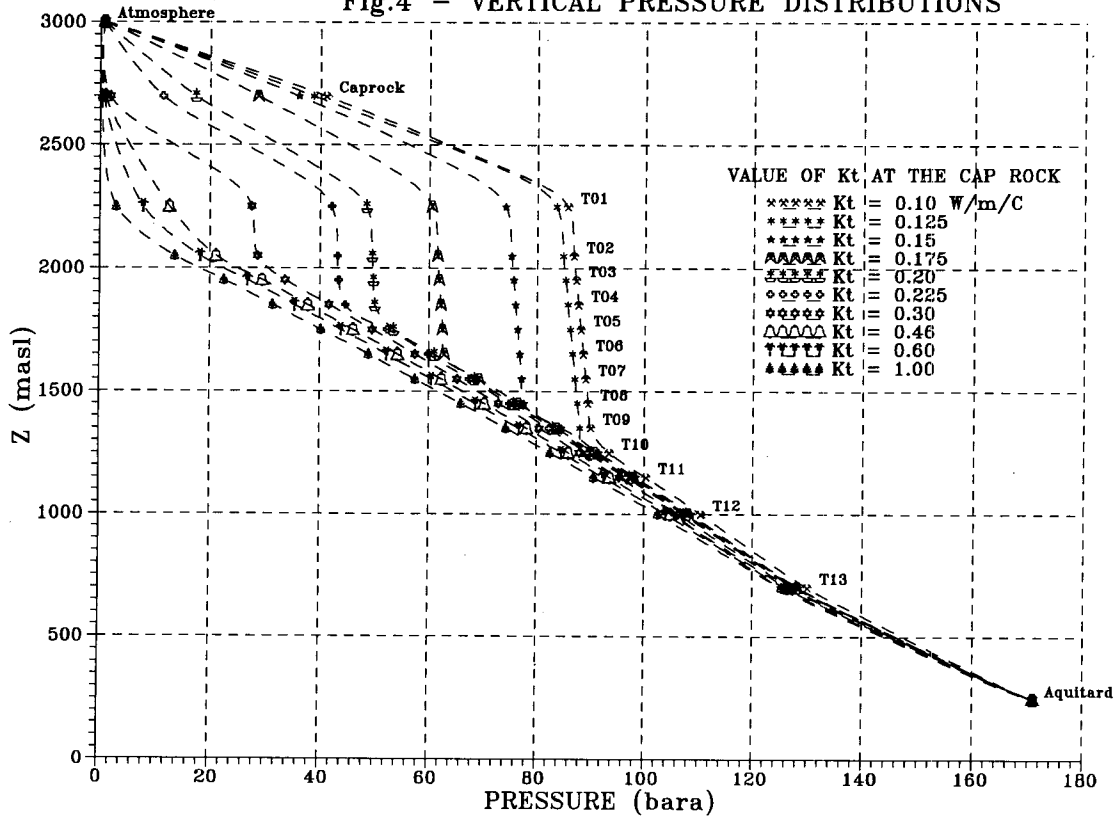


Fig.5 - VERTICAL TEMPERATURE DISTRIBUTIONS

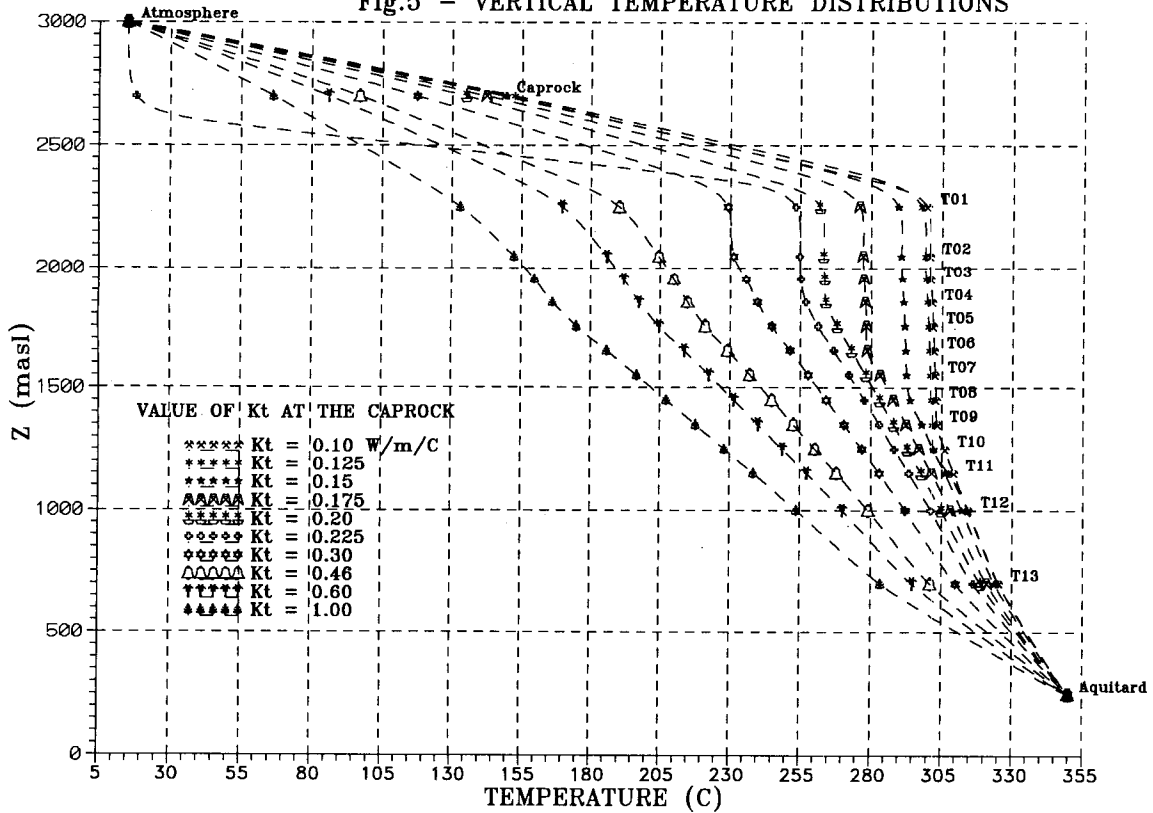


Fig.6 - VAPOR SATURATION AND Kt.

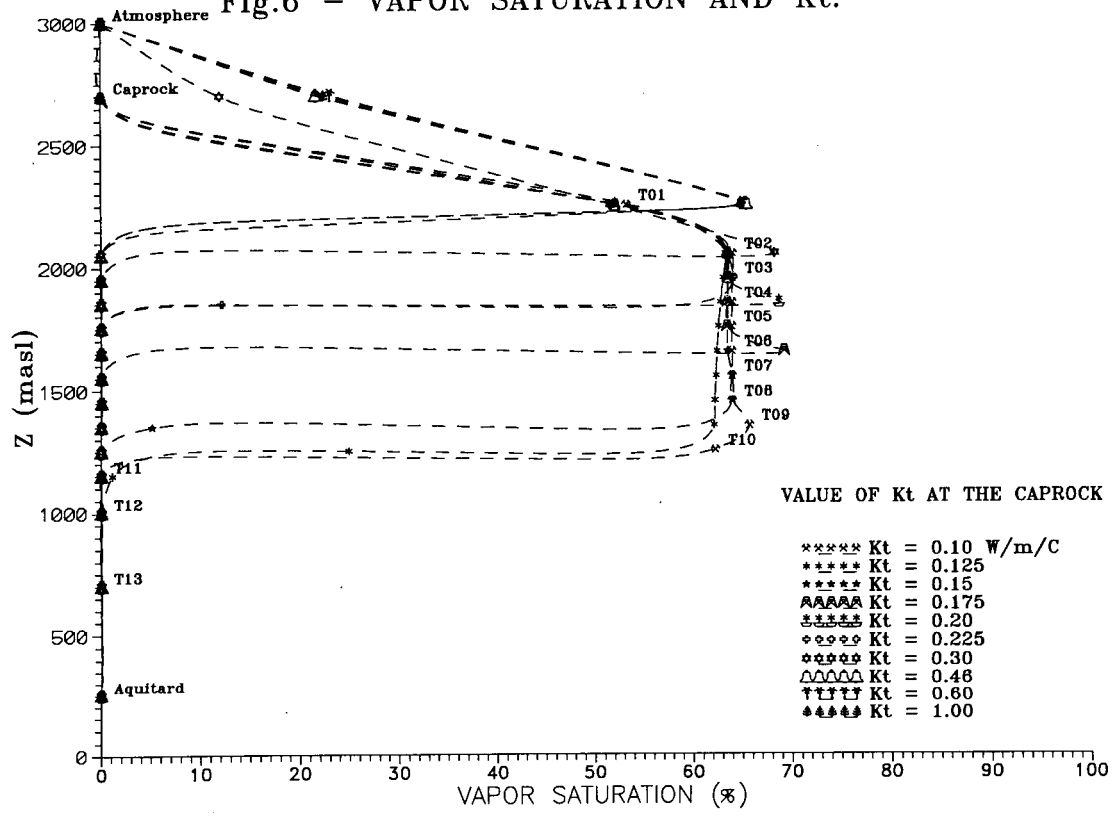


Fig.7 - PARTIAL PRESSURE OF CO2 AND Kt .

