MULTIDISCIPLINARY DATA SUBSTANTIATE VAPLIQ MODEL OF THE LOS AZUFRES GEOTHERMAL SYSTEM

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ABSTRACT

En este trabajo revisamos y expandimos nuestro modelo vapliq del sistema hidrotermal de Los Azufres. Presentamos datos que delinean las distribuciones verticales de conductividad térmica y densidad total de las formaciones. Ambas distribuciones indican un cambio brusco de las propiedades de las formaciones en la frontera entre la zona predominada por líquido y la predominada por vapor. Esto apoya nuestra inferencia previa de que debe existir un contraste substancial de permeabilidad entre las capas predominadas por líquido y por vapor del sistema. Presentamos también la distribución vertical observada de saturación de líquido, inferida a partir de las composiciones químicas de fluidos del yacimiento y de registros de pozos; usamos esta distribución conjuntamente con el perfil vertical de presión observado, para calibrar los parámetros termofísicos del sistema. Esta calibración contra ambos perfiles aumenta significativamente la confiabilidad del modelo. El nuevo modelo predice valores de permeabilidad vertical de aproximadamente 0.1×10^{-18} y 80×10^{-18} m^2 para las capas predominadas por líquido y por vapor respectivamente. La baja permeabilidad de la zona predominada por líquido y el contraste de permeabilidad aparecen como las razones principales de las características vapliq que presenta el sistema. Además de la distribución de permeabilidad vertical, el modelo provee estimaciones de los flujos de masa y calor, y de las funciones de permeabilidad relativa del sistema. El nuevo modelo representa consistentemente un enorme conjunto de datos multidisciplinarios.

INTRODUCTION

In previous work (Iglesias and Arellano 1988a, 1988b) we discussed vapliq hydrothermal systems and the thermohydrological conditions for their existence. (The central, upflowing part of vapliq systems is a stack with a compressed-liquid layer at the base, a liquid-dominated zone in the middle, and a vapor-dominated cap). We also presented a vapliq model of the Los Azufres system (natural state), and on its basis concluded that a substantial vertical permeability contrast must exist between the vapor- and the liquid-dominated layer, the smaller permeability corresponding to the later. Assuming a homogeneous vertical distribution of thermal conductivity we estimated permeability values and other thermohydrological parameters of the system.

Though this model was consistent with a number of observations (downhole pressures, stabilized temperatures, geothermometrical estimates, hydrothermal alteration as deduced from drill cuttings, and the ranges of permeability and thermal conductivity found in laboratory measurements of drill cores), the reliability of the estimates remained somewhat questionable because: (a) only the observed vertical pressure profile was fitted in detail, and it is known that pressure fitting alone may be misleading if applied to standard-quality observations; (b) we knew, from theoretical calculations, that non-homogeneous thermal conductivity distributions, if applicable to Los Azufres, could require significant revisions of our estimates; and (c) no direct evidence substantiating a sudden change of formation properties at the boundary between the vapor- and liquid-dominated layers had been found at the time of our previous work.

THE MODEL

We consider a 1-D vertical, steady-state scenario, based on generally accepted conceptual models of the natural states of liquid- and vapor-dominated geothermal systems. We model only the central portion of the system where there is a net mass upflow, and where mass and heat transfer have only vertical components.

Based on our earlier results (Iglesias and Arellano 1988a, 1988b) we assume a step distribution of vertical permeability, with the lower value corresponding to the liquid-dominated layer. At the base of the system there is hot compressed liquid that ascends isoentalpically (e.g., White, 1967). Eventually the compressed liquid reaches its boiling point and a 2-phase, liquid-dominated layer develops. This layer extends upwards until it is replaced by a vapor-dominated cap, starting at the permeability discontinuity.

The model equations are given in Iglesias and Arellano (1988a). They represent 2-phase, steady-state conservation of mass, momentum and energy, and are complemented by appropriate constitutive equations. Heat flux Q and mass flux F are constants of the system. This set of equations is numerically solved. The present numerical code allows arbitrarily varying distributions of thermal conductivity.

LIQUID SATURATION PROFILE

In-situ liquid saturations for 15 wells representative of ascending flow in the system were derived from 63 fluid samples (Table 1). A subset of these results appeared in Nieva et al. (1987).

Table 1. Sampling for liquid saturation

Well	Samples	Well	Samples
Az-5	9	Az-32	1
Az-6	8	Az-33	1
Az-9	3	Az-34	1
Az-16AD	8	Az-35	1
Az-17	9	Az-36	3
Az-19	4	Az-37	1
Az-22	5	Az-38	3
Az-28	6		

Liquid saturations were computed with a method originally devised by Giggenbach (1980) and modified by Nieva et al. (1985). This modification was necessary to apply the method to wells with high concentrations of non-condensable gases in their total discharges. Briefly, liquid saturation is computed from the seeming distortion of the relative proportions of chemical species participating in the Fischer-Tropsch reaction in the reservoir.

The method requires estimates of reservoir temperature for each well (feed zone). The required temperature estimates were obtained from cation geothermometers, temperature logs, pressure logs and 2-phase assumption, and extrapolation to zero flowrate at computed bottomhole conditions. These temperature estimates were independent from the results generated by the vap-liq model described in the preceding section. This prevents circular bias. The sensitivity of the computed liquid saturation to the assumed reservoir temperature is relatively mild, e.g., a temperature error of ±5°C typically results in a 5% variation in liquid saturation.

The locations of the feed zones were obtained from records of drilling fluid losses, temperature logs, pressure logs, well completions and lithologic column records.

Figure 1 represents the resulting liquid saturation profile, and the associated uncertainties.

FORMATION PROPERTIES

As stated, previous work indicated that the vertical permeability distribution may be approximated by a step function with its discontinuity marking the location of the boundary between the liquid-dominated layer and the vapor-dominated cap. The corresponding permeability values were estimated in this work by fitting model-generated profiles to the observed pressure and liquid saturation profiles (see following section).

Thermal conductivity was recently measured in 16 drill cores from Los Azufres (Iglesias et al., 1987; García et al., 1988). Figure 2 presents these results in terms of elevation. We discern two distinct trends in the data. The elevation of the boundary between both trends is strikingly coincident with that at which the liquid-dominated layer turns into the vapor-dominated cap, as attested by the observed pressure profile (Fig. 3). The upper trend of Fig.2 has a linear correlation coefficient r=-0.7988, with a confidence level (CL) greater than 99.5%. For the lower trend the corresponding figures are r=-0.8617, CL>99.5%. Note that the discontinuity in thermal conductivity is clearly observable in well Az-3 (cores 3-1, 3-4 and 3-5) and in well Az-26 (cores 26-2 and 26-3).

The percentage of total hydrothermal alteration of 20 drill cores from Los Azufres, which include the cores of the preceding paragraph, were also determined recently (Iglesias et al., 1987). The hydrothermal alteration of the cores lying in the vapor-dominated layer correlates well (r=-0.8075, CL>99.5%) with elevation, as illustrated in Fig. 4. No significant correlation of total alteration with elevation was found for the cores in the liquid-dominated zone.

Coincidently, thermal conductivity correlates well (r=0.9917, CL>99.5%) with total hydrothermal alteration in the vapor-dominated cap (Fig. 5), and no significant correlation was found between these variables in the liquid-dominated layer.

Bulk density was measured in the same 20 drill cores (Iglesias et al., 1987). The corresponding results are plotted against elevation in Fig. 6. Two trends are also discernible in these data. In the vapor-dominated layer, bulk density correlates linearly with elevation ($r=-0.6452$) with a CL>98.64%. A stronger correlation ($r=-0.8654$, CL>99.98%) between these variables is found in the liquid-dominated zone.

These results clearly substantiate the notion that a sharp change in formation properties exists at the boundary between the liquid- and the vapor-dominated layers in Los Azufres, whatever its cause. The postulated vertical permeability contrast is consistent with such change.

MODEL RESULTS AND DISCUSSION

The thermohydrological conditions of the system were obtained by trial and error (e.g., Iglesias and Arellano, 1988a, 1988b), by matching model profiles to the observed pressure (Fig. 3) and liquid saturation (Fig. 1) profiles. The main parameters thus estimated are Q, the net (vertical) heat flux; F, the net (vertical) mass flux; k(z), the distribution of vertical permeability in terms of altitude z; k_L and k_V, the liquid and vapor relative permeabilities; S_{LR} and S_{VR}, the liquid and vapor irreducible saturations; and p(z) and S(z), the pressure and liquid saturation vertical profiles, respectively.

In this model we take as known input parameters p_B, the pressure at the boiling point of the system; z_B, the elevation of the boiling point; and K(z), the vertical distribution of thermal conductivity. The input parameters also include trial values of Q, and trial functions k(z), and $k_L(S)$ and $k_V(S)$, where S is liquid saturation.

The boiling point of the system is p_B=8.6 MPa, and its elevation z_B=1300 m a.s.l. (Iglesias et al., 1985). The variation of thermal conductivity along the liquid-dominated layer is small (Fig. 2). Thus a simple model is to set K=constant in the liquid-dominated layer, and K linearly varying with z, in the vapor-dominated cap, as in Fig. 2. Trial values for Q, k_{down} and k_{up} (the values of k(z) in the liquid- and vapor-dominated layers respectively) were suggested by our previous work (Iglesias and Arellano, 1988a; 1988b). For the relative permeability functions we tried Corey- and X-type curves; only X-type curves resulted in reasonable matches of the observed pressure and liquid saturation profiles.

Our best match for the model of the preceding paragraph is shown in Figs. 3 and 7. The corresponding model parameters are $Q=0.1$ Wm^{-2}, $F=0.4$ $kgm^{-2}s^{-1}$, $k_{down}=1.0\times10^{-19}$ m^2, $k_{up}=0.8\times10^{-16}$ m^2, $K_{down}=1.6$ $Wm^{-1} \cdot C^{-1}$, K_{up}=variable, $S_{LR}=0.20$, $S_{VR}=0.00$. The match to the pressure profile is excellent. The match to the liquid saturation profile looks promising but not quite satisfactory: the synthetic profile seems too low in the liquid-dominated layer. Despite this, it is interesting to note that the position of the nearly vertical line matching the liquid saturation of the vapor-dominated layer is totally determined by the value assigned to S_{LR}: lower (higher) values of this parameter shift the nearly vertical line to the left (right). Thus, we interpret the approximately constant observed liquid saturation of the steam cap as resulting mainly from the formation's irreducible liquid saturation. The value indicated for Q is consistent with that inferred from stabilized temperatures in the caprock (Iglesias et al., 1988a, 1988b). The small value obtained for F is qualitatively consistent with the mild (as compared with other geothermal fields) surface manifestations, which consist exclusively of fumaroles.

An improved match to the liquid saturation profile is presented in Fig. 8; the corresponding pressure results are indistinguishable from those of Fig. 3. This match was obtained using the same model parameters as before, except that K_{down} was allowed to vary as in Fig. 2. The reason for the improvement can be understood with the help of Fig. 9. The (constant) heat flux is the sum of a conductive and a convective component. Heat flow is overwhelmingly conductive in the liquid-dominated layer, due to its small permeability. Thus, even small variations of thermal conductivity (and therefore of the conductive flux) in this layer, translate in greater relative changes of the convective flux, which is mediated by liquid saturation via the relative permeability functions.

The present results confirm, refine and enlarge those of our previous work. The present model is consistent with a large body of multidisciplinary evidence, including pressure, temperature and drilling logs (used to define the observed pressure and liquid saturation profiles), stabilized temperatures, discharge enthalpies, chemical composition of total discharges (via the inferred liquid saturations), cation geothermometers, hydrothermal alteration as deduced from drill cuttings and cores [e.g., correlations of total hydrothermal alteration with thermal conductivity and with elevation; consistency of the 3-D distribution of calcite deposition with the inferred 2-phase layers (Iglesias et al., 1986a)], and measurements of formation density and thermal conductivity in drill cores (this paper). Furthermore, the permeability values predicted by this model are consistent with the laboratory measured matrix permeability of drill cores, which ranges from less than 2×10^{-18} m^2 to about 400×10^{-18} m^2 (Iglesias et al., 1986b). This ample multidisciplinary consistency lends strong support to the model.

SUMMARY AND CONCLUSIONS

This paper contributes previously unpublished vertical distributions of thermal conductivity, formation bulk density, and observed liquid saturation, for the central, upwelling zone of the Los Azufres geothermal system. These contributions were used to refine a previous model of the system.

The present model is strongly supported by ample multidisciplinary evidence.

The observed vertical distributions of formation properties, pressure and liquid saturation, and the model results, consistently indicate the existence of a sharp change in formation properties at the boundary between the liquid-dominated layer and the vapor-dominated cap. Our model predicts vertical permeability values of about 0.1×10^{-18} m^2 for the liquid-dominated layer and of about 80×10^{-18} m^2 for the steam cap. The low permeability of the liquid-dominated layer and the existence of the inferred permeability contrast appear as the main reasons for the vapliq characteristic displayed by this geothermal system.

The model also indicates that the observed liquid saturation in the steam cap, $S_L=0.2$, reflects the formation's irreducible liquid saturation S_{LR}. The model furthermore indicates X-type relative permeability functions and $S_{VR}=0$.

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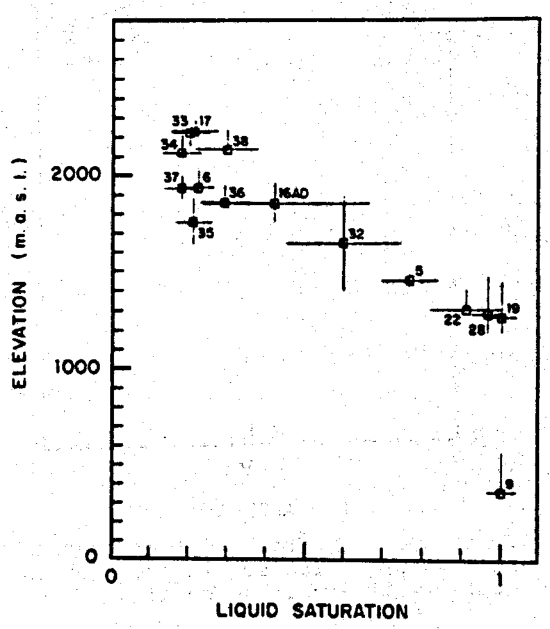

Fig. 1. Observed distribution of liquid saturation in the central, upflowing part of the system. Numbers identify wells.

Fig. 1. Distribución de saturación de líquido observada en la zona central, de ascenso de fluidos del sistema. Los números identifican pozos.

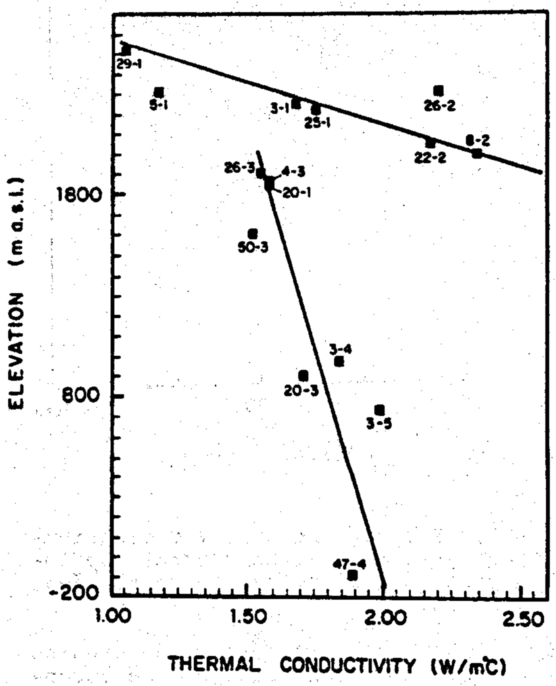

Fig. 2. Vertical distribution of thermal conductivity, from drill cores.

Fig. 2. Distribución vertical de conductividad térmica, inferida de núcleos de perforación.

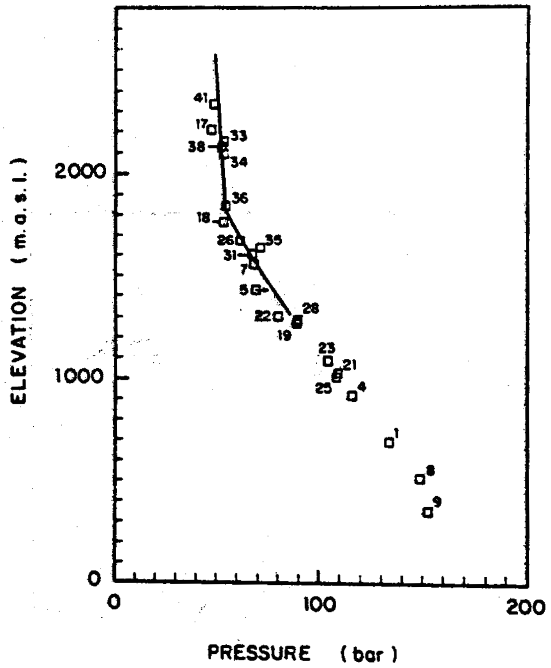

Fig. 3. Fit to the observed distribution of pressure in the central, upflowing part of the system. Numbers identify wells.

Fig 3. Ajuste del perfil de presión observado en la zona central, de ascenso de fluidos del sistema. Los números identifican pozos.

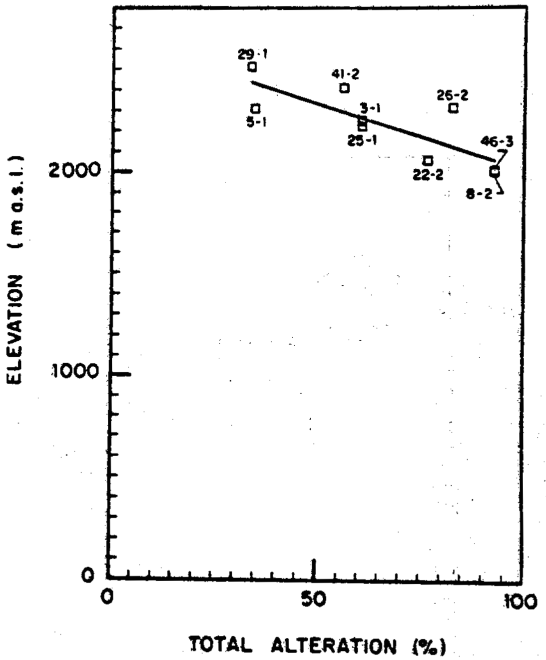

Fig. 4. Total hydrothermal alteration in the vapor-dominated layer. Numbers identify (well)-(core number).

Fig. 4. Alteración hidrotermal total en la capa predominada por vapor. Los números identifican (pozo)-(núcleo).

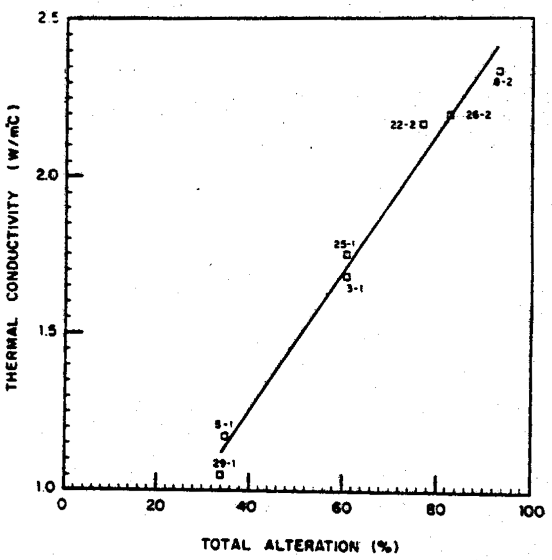

Fig. 5. Correlation between thermal conductivity and total hydrothermal alteration in the vapor-dominated layer. Numbers identify (well)-(core number).

Fig. 5. Correlación entre conductividad térmica y alteración hidrotermal total en la capa predominada por vapor. Los números identifican (pozo)-(núcleo).

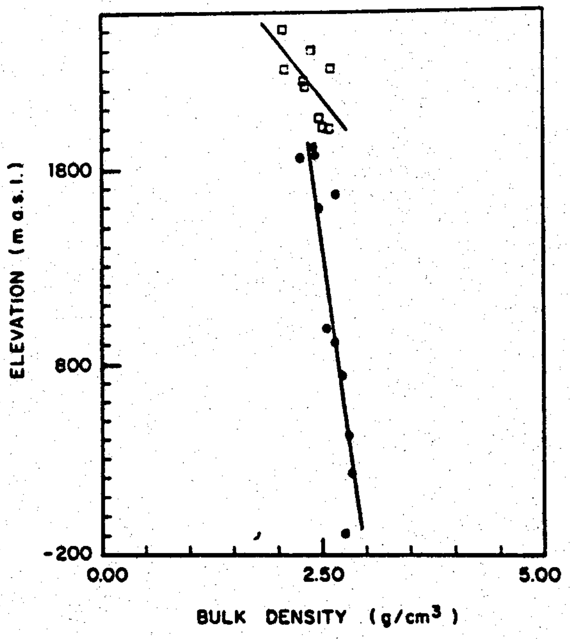

Fig. 6. Vertical distribution of bulk density, from dill cores.

Fig. 6. Distribución vertical de densidad total, inferida de núcleos de perforación.

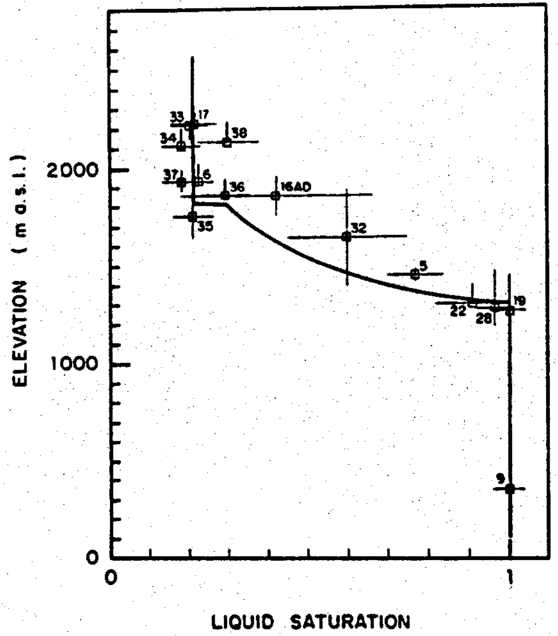

Fig. 7. Fit to the observed distribution of liquid saturation, taking K_{down}=1.6 Wm^{-1}°C^{-1}.

Fig. 7. Ajuste de la distribución observada de saturación de líquido, tomando K_{down}=1.6 Wm^{-1}°C^{-1}.

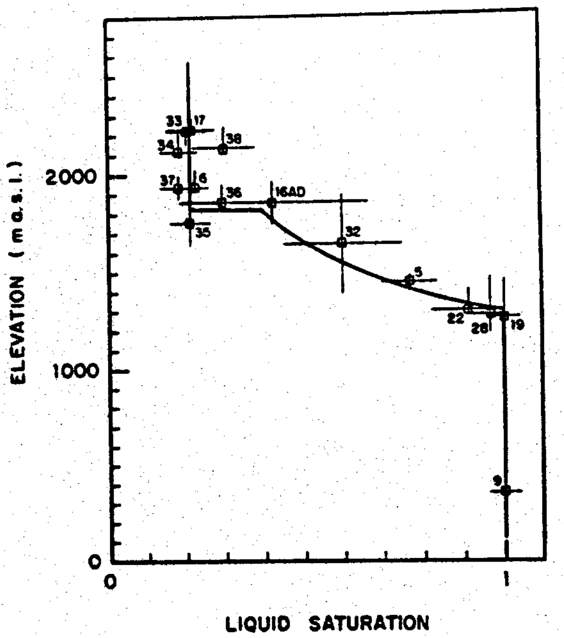

Fig. 8. Improved fit to S_L; K_{down} was allowed to vary as in Fig. 2.

Fig. 8. Ajuste mejorado de S_L; K_{down} varía como en la Fig. 2.

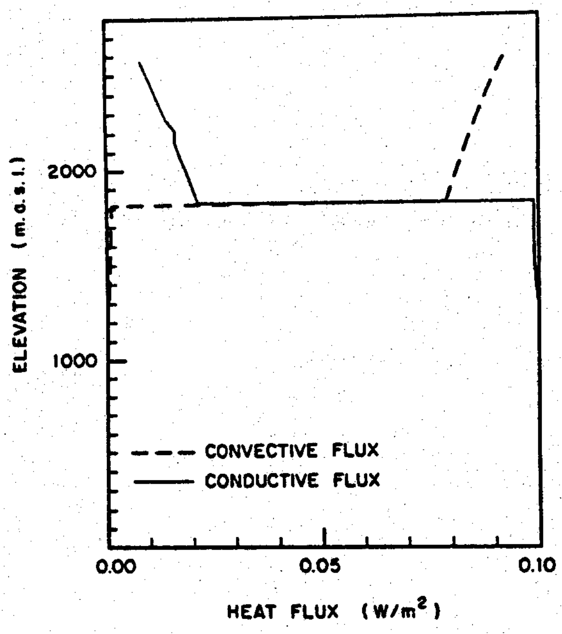

Fig. 9. Conductive and convective components of the heat flux.

Fig. 9. Componentes conductiva y convectiva del flujo térmico.