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A CONCEPTUAL MODEL OF THE LOS HUMEROS, (MEXICO), GEOTHERMAL RESERVOIR IN ITS NATURAL STATE.

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ABSTRACT

With data from 42 wells from the Los Humeros geothermal field the corresponding values of pressure and temperature for the unperturbed fluids of the reservoir were derived. On the basis of the analyzed data, reservoir models in one and two dimensions for the initial state were developed. The models reveal the existence of at least two reservoirs. The first and shallower one is located between 1025 m. a. s. l. and 1600 m. a. s. l. and it is classified as liquid-dominant. The pressure profile of this stratum corresponds to a 300 and 330°C boiling water column. The second reservoir is located between 850 m. a. s. l. and 100 m. a. s. l. and it is defined as a low liquid saturation reservoir. Temperatures for this zone were estimated between 300°C and 400 °C.

1. INTRODUCTION.

The Los Humeros geothermal field is located in the eastern portion of the Mexican Volcanic Belt (19° 40´ latitude N, 97° 25´ longitude W), approximately 200 km from Mexico city (Fig. 1). In 1968, the Comisión Federal de Electricidad (CFE) carried out the first geological, geochemical and geophysical studies, (Mena and González-Morán, 1978; Pérez-Reynoso, 1978; Yañez-García et al, 1979; Palacios-Hertweg and García-Velázquez, 1981). In 1982 the first deep well was drilled with the purpose of confirming the results of the previous studies. In 1990 the commercial exploitation of the resource began with the installation of the first 5 MWe unit. To date near 40 wells have been drilled (Figure 2) and 7 units of 5 MWe were installed, (Quijano and Torres, 1995).

For the Los Humeros geothermal field some conceptual and mathematical models have been developed (Viggiano and Robles, 1988 a, b; Torres, 1995, Cedillo, 1997; Prol-Ledesma, 1998). However, in 1998 the CFE technical staff decided to carry out an investigation in order to: a) to confirm the existence of one or more reservoirs in the system; b) to determine the initial conditions of the reservoirs; c) to define the origin of acid fluids in the reservoir; d) to define a strategy that permits the exploitation of such fluids. With the objective of clearing up some of the aspects previously mentioned, the Gerencia de Proyectos Geotermoeléctricos and the Instituto de Investigaciones Eléctricas technical staffs decided to participate jointly in a project to develop a conceptual model for the Los Humeros geothermal system at initial state conditions (Arellano et al, 1998).

In this work, results of analyzing drilling information, pressure and temperature profiles measured during well warmup, undisturbed reservoir temperatures and production characteristic curves for 40 wells are presented with the purpose of determining the depths at which the wells penetrate permeable zones where, the measurements or estimations reflect the actual reservoir conditions. The results of the analysis of every well were utilized as a base to estimate the initial pressure and temperature distributions for the geothermal reservoir. The results were integrated in one and two dimensions models which were then used to analyze the main characteristics of the Los Humeros hydrothermal system.

2. GEOLOGICAL SETTING.

The geology of the Los Humeros has been described by several authors, (Pérez-Reynoso, 1978; Yáñez-García, et al, (1979); Ferriz and Mahood (1984); Viggiano and Robles (1988 a, b) and Cedillo (1997). The local basement is formed by a Paleozoic metamorphic complex, chlorite-muscovite shales, a Mesozoic folded sedimentary sequence, a Lower Tertiary syenitic and granodioritic intrusions and Pliocene andesites.

It is considered that the initial volcanic activity in the area is represented by andesitic and ferrobasaltic lavas of the Teziutlán Formation, whose age varies from 3.50 to 1.55 Ma. However, most of the volcanic units are less than 0.5 Ma, and they were accompanied by the formation of calderic structures (Figure 2). The collapse of the The Humeros Caldera was caused by the eruption of the Xáltipan ignimbrite (0.46 Ma). After the collapse, some silicic domes were formed (0.3 Ma). The Zaragoza ignimbrite emission (0.1 Ma) provoked the collapse of the Los Potreros caldera and andesites, basaltic andesites, lava, pumice and ash emissions (0.08 to 0.04 Ma) created the Xalapazco structure. The more recent volcanic activity is represented by olivine basaltic components (0.02 Ma).

CFE geologists have performed detailed studies of well cuttings to determine petrographic characteristics of the lithological units. Thus, the lithologic column of the field has been reconstructed, (Viggiano and Robles, 1988 a; Cedillo, 1997). In Table 1 a summary of the Los Humeros geology is shown. Figure 3 shows the 7 km long geological section L3 with a NNW-SSE direction. This section links the following wells: H-21, H-31, H-15, H-30, H-16, H-33, H-29, H-4, H-10, H-26 and H-6. Nine lithologic units, and also their thickness, the fault systems and the topography of the field basement are illustrated.

3. GEOCHEMICAL CHARACTERISTICS OF THE FLUIDS.

At wellhead conditions, the wells produce a small water fraction with exception of well H-1 that is located in the Corredor Xalapazco Maztaloya zone. It is difficult to classify the fluids since they appear to be mixed (Barragán et al, 1988) and have variable composition in time, (Tello, 1992;

Tello 1994). Also it is extremely difficult to reconstruct the composition of the reservoir liquid phase, due mainly to the large amount of condensed steam with high concentration of bicarbonate and sulfate and also because some of the wells have or have had contribution of fluids from more than one reservoir. The water produced is very diluted in ions and exhibits almost neutral pH at separating conditions. Some exceptions occurred as in wells H-4 and H-16 that are located in the Colapso Central (Central Collapse) zone and produced acid fluids that caused corrosion phenomena (Barragán et al, 1989; Gutiérrez-Negrín and Viggiano-Guerra, 1990; Truesdell, 1991).

4. METHODOLOGY.

In order to establish the natural pressure and temperature distributions the following methodology was used: 1) The permeable horizons in the wells were determined by the analysis of drilling information, pressure and temperature logs taken during well warmup, undisturbed reservoir temperatures and geological correlations; 2) The pressure profile of the undisturbed reservoir was reconstructed by the analysis of pressure logs, the application of the pivot method and pressure well test analysis; 3) The undisturbed temperature profile was inferred through the analysis of temperature logs and the estimation of recovered formation temperatures by Horner and Sphere methods, (Ascencio et al., 1994). The obtained pressure and temperature values were analyzed graphically (one and two dimensions) in order to reproduce the main characteristics of the Los Humeros geothermal system. In this first approach no correction by solutes content in the fluids was done.

5. RESULTS AND DISCUSSION.

5.1 Permeable Horizons.

In Figure 4, the location of the main feeding zones of wells in the L3 geological section are shown. Analysis of data of all the wells of the field (Arellano et al, 1998), shows that permeability occurs in the Augite andesites, hornblende andesites, basalts and metamorphic limestones. The limestones have the least primary permeability. However, a significant number of wells seems to be fed from that reservoir zone, implying that it has some fractures.

5.2 Pressure Distribution.

Once the horizons, in which the well and the reservoir are in contact, were identified, the reconstruction of the undisturbed reservoir pressure profile was done. The results of logs analysis taken with the well closed after drilling and before starting production are shown in Figure 5. An important feature displayed by the data is the wide range of reservoir altitudes (1500 m), which is reflected in the reservoir vertical pressure distribution that varies from 89 bar to 176 bar. Thus, the Los Humeros offers an opportunity to study in detail the undisturbed geothermal reservoir vertical profile, for an extensive elevation range.

Figure 5 represents an overall unperturbed pressure – altitude profile of the field. A boiling point for depth (BPD) curve (e.g. Grant et al., 1982) has been matched to the data and shows high correlation from 1600 m.a.s.l. to approximately 1025 m. a. s. l. However, below 1025 m.a.s.l. a group of wells do not follow this behavior, presumably because the reservoir contains two-phase fluid with low liquid saturation (< 5-10%), and hence the pressure is vapor dominated (Truesdell and White, 1973). The nearly vertical profile may be represented by the following expression:

$$P = 177.5 - 0.0405Z \qquad (1)$$

where P is the pressure in bar and Z is the altitude in m. a. s. l. In Figure 6 the adjustment of the data to the BPD model and to the expression (1) is shown.

Thus, it can be concluded that in the Los Humeros geothermal system there exist at least two reservoirs. The shallower one is located between 1025 m. a. s. l. and 1600 m. a. s. l. and given the excellent agreement with the BPD it is defined as liquid-dominant, with a pressure profile corresponding to a hydrostatic gradient at a temperature of 300°C- 330 °C.

The second reservoir is located between 850 m. a. s. l. and 100 m. a. s. l. and is considered as a low liquid saturation reservoir. The pressure profile described by the expression (1) is intermediate between vapor-static and hydrostatic. This type of profile occurs when a counter-flow phenomenon is present. Vapor ascends, condenses at a certain depth and then flows as liquid water in the opposite direction (porous heat pipe).

The change of the pressure distribution slope at about 900 m. a. s. l. (Figure 6), suggests that the two reservoirs are separated by the relatively low permeability vitreous tuff layer.

From the pressure distribution it is suggested that the whole reservoir presents hydraulic continuity. The wells that depart the general behavior (H-2, H-5, and H-25) probably indicate the limit of the reservoir (well H-25 in the East, well H-2 in the Southwest and well H-5 in the West of the field).

As part of the study the analysis of 28 pressure well tests, that involved 18 wells of the field, was performed. In a number of tests it was possible to estimate the average reservoir pressure. In Figure 7 the one dimension vertical pressure profile versus the respective altitudes is presented. As it can be seen, the adjustment with the BPD model is acceptable.

In general, results obtained by the pressure well tests analysis agree well with results previously discussed for the upper reservoir.

5.3 Temperature Distribution.

Figure 8 shows the temperature estimated by the Sphere method for each well at the feed point; as well as its adjustment with the BPD model. Wells that show scattering (H-1, H-5, H-14 and H-25) are probably located in the limit or out of the exploitable reservoir. If these wells are not considered in the graph it can be observed a tendency of wells between 1025 m. a. s. l. and 1600 m.a.s.l. That corresponds to the upper reservoir discussed in the previous section. For these wells the temperature was estimated to be between 290°C and 330°C. This agrees reasonably well with the temperatures estimated by the hydrostatic gradient observed in the pressure profile (between 300°C and 330 °C). The wells that are found in the lower part, (elevations from 850 to

100 m.a.s.l.) show a higher temperature range, between 300°C and 400 °C. This probably reflected the complexity of the geothermal system and also the method limitations, since it is affected by all the aspects that have influence in the measured temperature profiles (cooling, boiling, measurement errors, etc.).

The results obtained through the temperature distribution agree reasonably well with the image of the reservoir obtained through pressure data. Both suggest the existence of a shallower liquid-dominant reservoir and at depth around the Colapso Central zone another low water saturation reservoir. The deep wells located in the Corredor Xalapazco- Maztaloya seem to contain a more significant fraction of liquid.

In Figure 9 the distribution of temperature for the L3 geological section is shown. In order to obtain the isotherms of the Figure 9 the spherical method was used considering the corresponding depths for every well. Here it can be clearly seen the ascent of hottest fluids in the Colapso Central zone (in Figure 9 this zone extends between the wells H-31 and H-10).

5.4 Hydrothermal Alteration.

The proportion and distribution of authigenic minerals (especially calcite and epidote) in the reservoir, show that there is a zone where the highest intensity of mineral alteration occurs. That corresponds to the zone of Teziutlán augite andesites (Unit 5; Table 1). In general, as depth increases the alteration in cuttings and cores decreases notably, indicating a low water:rock ratio.

In wells located in the Colapso Central zone, the absence of hydrothermal calcite (except for calcite in limestones) in deep levels is an indication of the low water:rock ratio. The contrary occurs in upper levels where calcite deposition is observed (Figure 10). In some wells calcite appears to depth in very low proportion, which is coincident with wells producing a mixture of fluids.

The same observation applies for epidote (Figure 11) whose distribution is an indication of the water:rock interaction, mainly in the upper andesite, to a temperature higher than 200 °C.

In Figure 12 a summary of the main characteristics of the previously described model for the Los Humeros geothermal field is shown.

6. SUMMARY AND CONCLUSIONS.

A considerable amount of data from 42 wells from the Los Humeros geothermal field was analyzed to infer the fluid thermodynamic state for the undisturbed reservoir.

On the basis of analyzed data and the distributions of pressure and resultant temperature, models in one and two dimensions were developed for undisturbed reservoir conditions. These models show that in the Los Humeros system at least two reservoirs exist. The shallower is located between 1025 m. a. s. l. and 1600 m.a.s.l., and given the excellent agreement with the BPD, it is defined as a liquid- dominant reservoir. The pressure profile of the shallower reservoir corresponds to a boiling water column at a temperature between 300 °C and 330 °C. A deeper reservoir is located between 850 m. a. s. l. and 100 m.a.s.l. and is considered to be a low water saturation reservoir. For the wells fed from this zone of the field, temperatures between 300°C and 400°C were estimated. The change of slope of the pressure distribution to 900 m. a. s. l. suggests that the two reservoirs are separated by the vitreous tuff layer (Unit 6).

In some of the wells the feeding zone was identified to be in limestones (with low primary permeability), this suggests that in certain places fractures occur permitting the fluids to flow.

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REFERENCES.

Arellano, V.M., García, A., Barragán, R.M., Izquierdo, G., Aragón, A., Nieva, D., Portugal, E., and Torres, I., 1998. *Desarrollo de un modelo básico actualizado del yacimiento de Los Humeros, Puebla*. Report IIE/11/11459/I01/F for the CFE, Instituto de Investigaciones Eléctricas, Temixco, Mor., 450 p.

Ascencio, F., García, A., Rivera, J. and Arellano, V.M., 1994. Estimation of undisturbed formation temperatures under spherical-radial heat flow conditions. *Geothermics*, Vol. 23, No. 4, pp. 317-326.

Barragán, R. M., Santoyo E., Nieva, D., Portugal, E. and Verma M. P., 1988. *Caracterización de yacimientos geotérmicos mediante la determinación de parámetros físico-químicos*. Internal Report IIE/11/2386/I 01/F, Instituto de Investigaciones Eléctricas, Temixco, Mor., 250 p.

Barragán, R.M., Cervantes, M., Díaz, R., Garduño, V., González, E., Holguín, S., Meza, F., Nieva, D., Oliver, R., Rosas, N., and Sampedro, J., 1989. *Caracterización del fenómeno de corrosión-obturación en pozos de Los Humeros*. Report IIE/11/3753/I for the CFE, Instituto de Investigaciones Eléctricas, Temixco, Mor., 83 p.

Cedillo, F., 1997. *Geología del subsuelo del campo geotérmico de Los Humeros, Pue*. Internal Report HU/RE/03/97, Comisión Federal de Electricidad, Gerencia de Proyectos Geotermoeléctricos, Residencia Los Humeros, Puebla, 30 p.

Ferriz, H. and Mahood, G. A., 1984. Eruption rates and compositional trends at The Humeros volcanic center, Puebla, Mexico. *J. Geophys. Res*., Vol. 89, pp. 8511-8524.

Grant, M. A., Donalson, G. and Bixley, P.F., 1982. *Geothermal Reservoir Engineering*. Academic Press, New York, 331 p.

Gutiérrez, L. C. and Viggiano J. C., 1990. Corrosion and scaling in well H-16 of the Los Humeros geothermal field. *Geoth. Res. Counc. Trans*., Vol. 14, pp. 1591-1598.

Mena, M. and González-Morán T., 1978. Regional gravity of The Humeros volcanic area. *Geofísica Internacional*, Vol. 17, pp. 429-443.

Palacios-Hertweg, L. and García-Velázquez, H., 1981. *Informe geofísico del proyecto geotérmico Los Humeros – Derrumbadas, estados de Puebla y Veracruz*. Internal Report, Comisión Federal de Electricidad, 96 p.

Pérez-Reynoso, J., 1978. Geología y petrografía de Los Humeros. *Geomimet*, Vol. 91, pp. 97-106.

Prol-Ledesma, R.M., 1998. Pre- and post-exploitation variations in hydrothermal activity in Los Humeros geothermal field, Mexico. *J. Volc. and Geoth. Res*., Vol. 83, pp. 313-333.

Quijano, J.L. and Torres, M., 1995. The Los Humeros geothermal reservoir, a case of very high temperature system. *Proc. World Geothermal Congress 1995*, Florence, Italy, 18-31 May 1995, Vol. 3, pp. 1569-1573.

Tello, H. E., 1992. Características geoquímicas e isotópicas de fluidos producidos por pozos del campo geotérmico de Los Humeros, Puebla. *Geotermia Rev. Mex. Geoen*. Vol. 8, pp. 3-48.

Tello, E., 1994. *Características geoquímicas de agua y gases de Los Humeros, Pue. I: Implicaciones de equilibrio*. Internal report CFE GQ-010-94, Morelia Mich., 25 pp.

Torres, M., 1995. Characterization of the reservoir of the Los Humeros, Mexico, Geothermal Field. *Proc. World Geothermal Congress 1995*, Florence, Italy, 18-31 May 1995, Vol. 3, pp. 1561-1567.

Truesdell, A. H. and White, D. E., 1973. Production of superheated steam from vapor-dominated geothermal reservoirs. *Geothermics*, Vol. 2, No. 3-4, pp. 154-173.

Truesdell, A. H., 1991. Origins of acid fluids in geothermal reservoirs. *Geoth. Res. Coun. Trans*. Vol. 15, pp. 289-296.

Viggiano, J.C. and Robles, C., 1988 a. Mineralogía hidrotermal en el campo geotérmico de Los Humeros, Pue., I: Su uso como indicadora de temperatura y del estado hidrológico. *Geotermia Rev. Mex. Geoen.,* Vol. 4, No. 1, pp. 15-28.

Viggiano, J.C. and Robles, C., 1988 b. Mineralogía hidrotermal in el campo geotérmico de Los Humeros, Pue., II: Geometría del yacimiento. *Geotermia Rev. Mex. Geoen.,* Vol. 4, No. 1, pp. 29-40.

Yañez-García, C., García-Durán, S. and Casique-Vásquez, J., 1979. Geothermal exploration in the Los Humeros – Derrumbadas area. *Geoth. Res. Coun. Trans*., Vol. 3, pp. 801-803.

Table 1. Geology of the Los Humeros system, (Cedillo, 1997).

Lithologic Unit	Description	Permeability	Hydrogeology
1	Pumice, Basalts and Andesites	High	Cold and hot superficial aquifers
2	Lithic Tuffs and Zaragoza Ignimbrites	Medium	Possible aquifer
3	Xaltipan Ignimbrites	Low to None	Aquiclude
4	Intercalation of Andesites and Ignimbrites	Low	Aquiclude
5	Teziutlán Augite Andesites	Medium	Shallower geothermal reservoir
6	Humeros Vitreous Tuff	Low	Aquitard
7	Hornblende Andesite	Medium	Deeper geothermal reservoir
8	Basalts	Medium	Deeper geothermal reservoir
9	Limestone, Metamorphic Limestone and Intrusives	Low	Aquitard

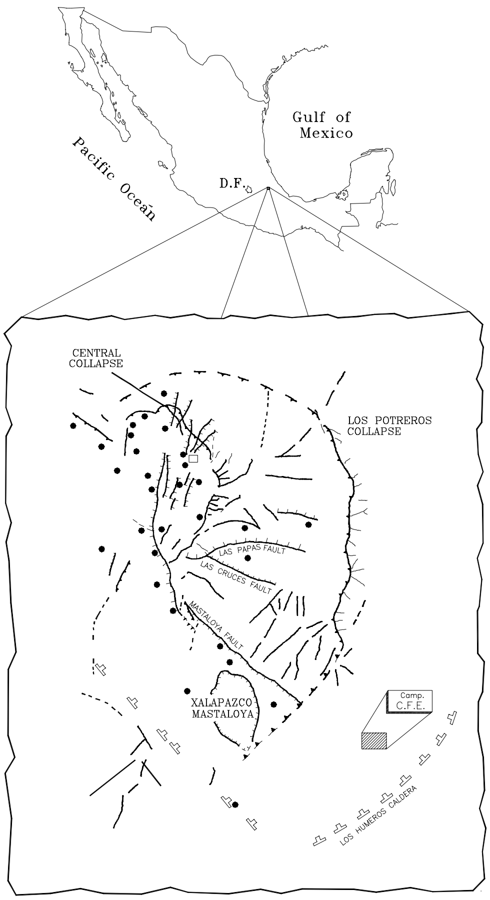

Figure 1.– Location of the Los Humeros geothermal field.

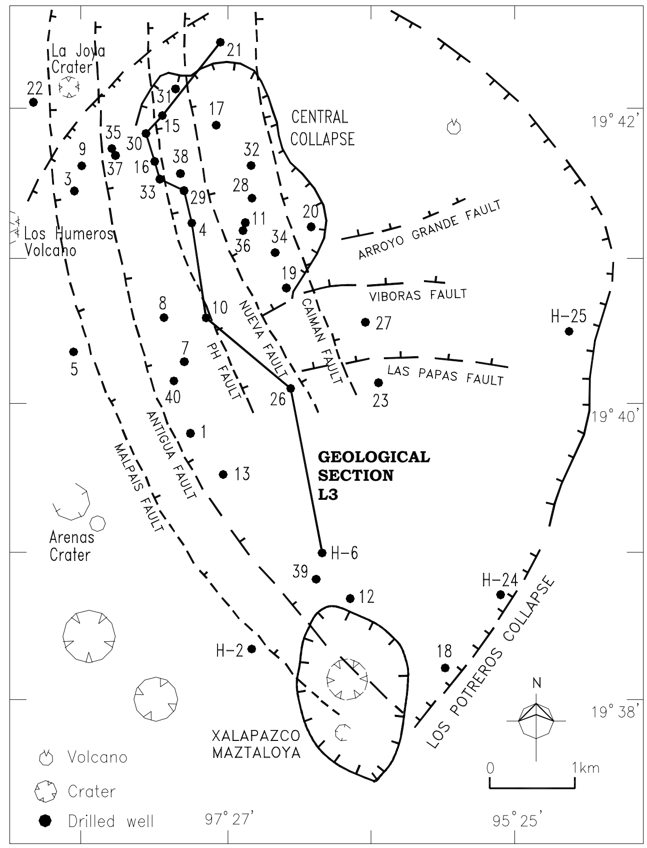

Figure 2.– Map of the Los Humeros geothermal field the main faults, structures and well locations are also shown.

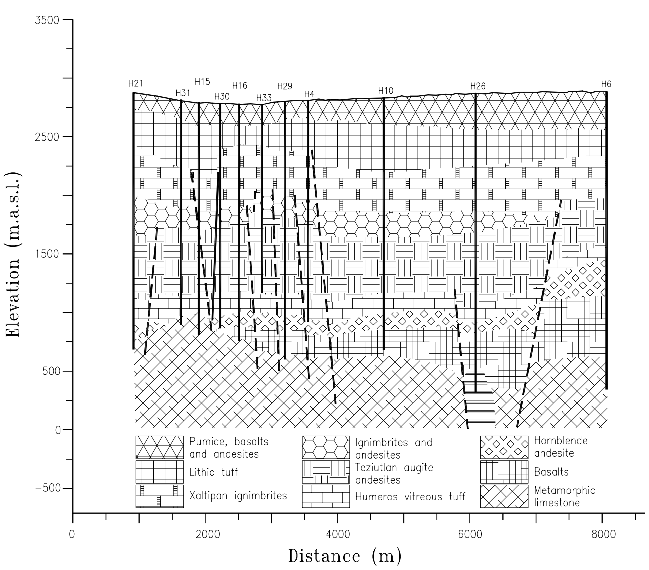

Figure 3.– L3 geological section with NNW-SSE direction and 7 km lenght (Cedillo, 1997).

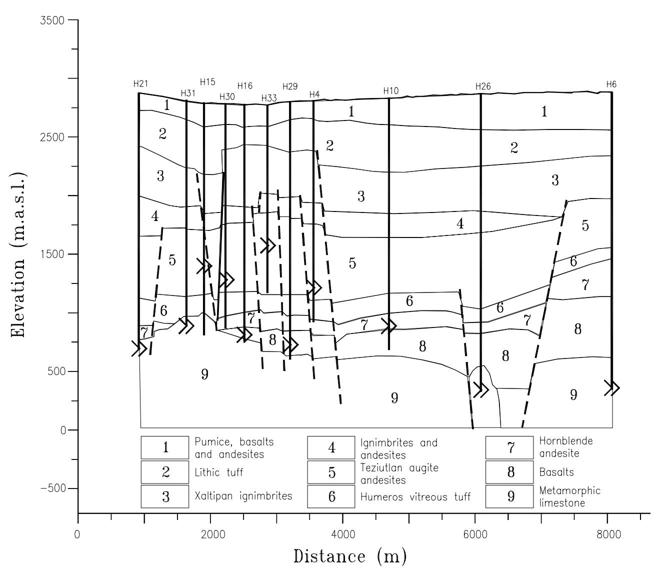

Figure 4.– L3 geological section showing the main permeable horizons.

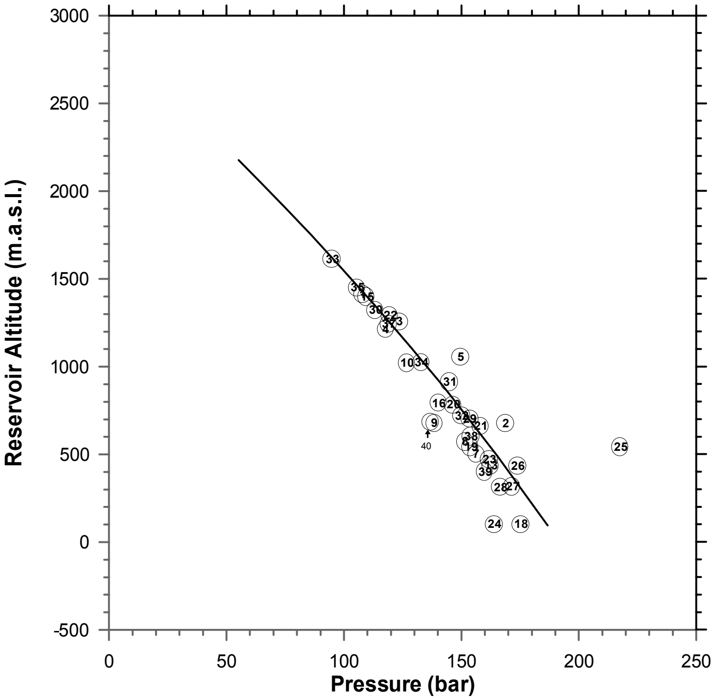

Figure 5.- Unperturbed pressure-altitude profile. The solid line represents BDP model.

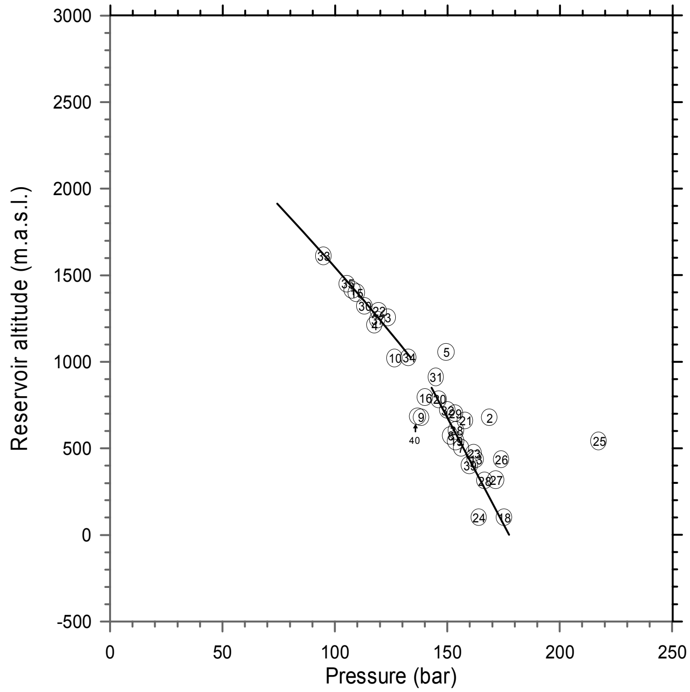

Figure 6.- Unperturbed pressure-altitude profile estimated using well pressure logs.

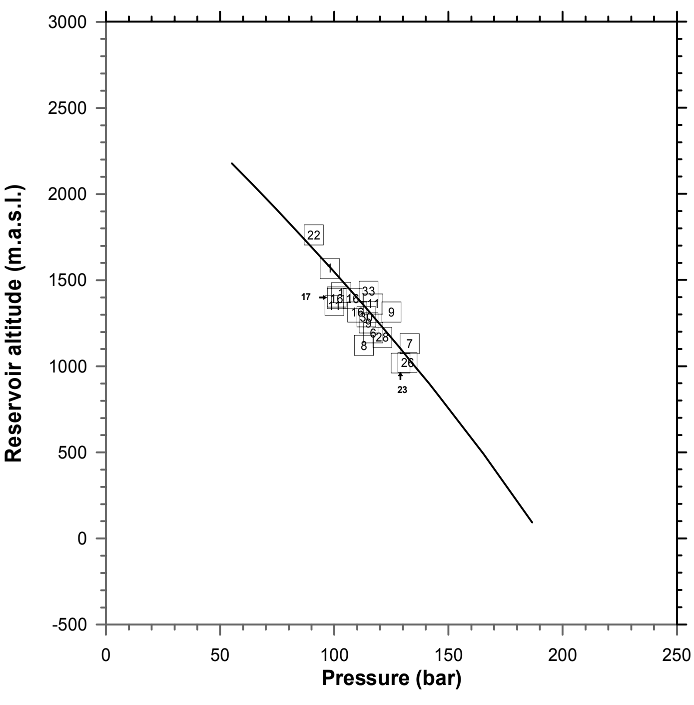

Figure 7.- Unperturbed pressure-altitude profile estimated using well test analysis.

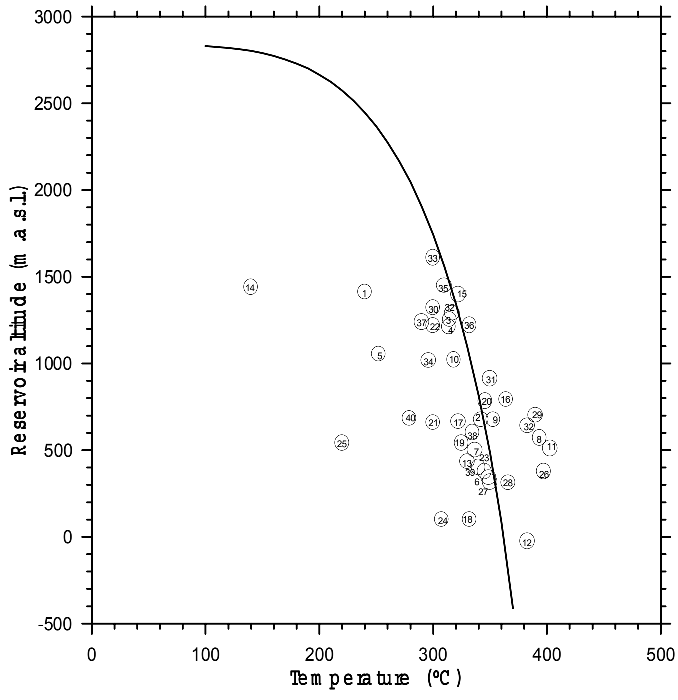

Figure 8.- Temperature-altitude profile estimated by the Sphere method the solid line represents BDP model.

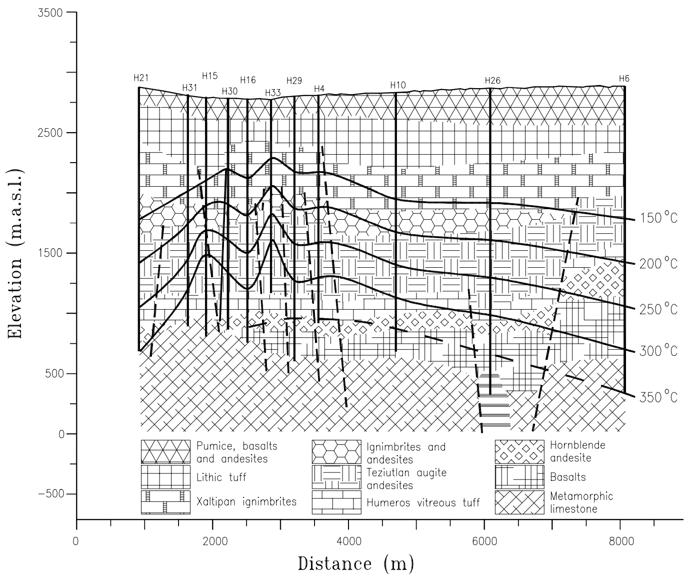

Figure 9.- Temperature distribution in geological section L3. Temperatures were estimated by the Sphere method.

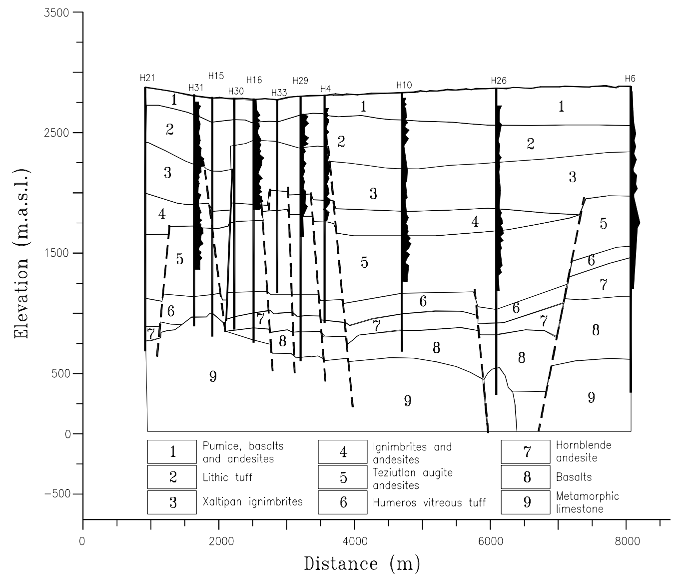

Figure 10.- Calcite distribution on geological section L3. Dark area represents the relative percentage of calcite. The maximum thickness corresponds to 20% of calcite in well H-6.

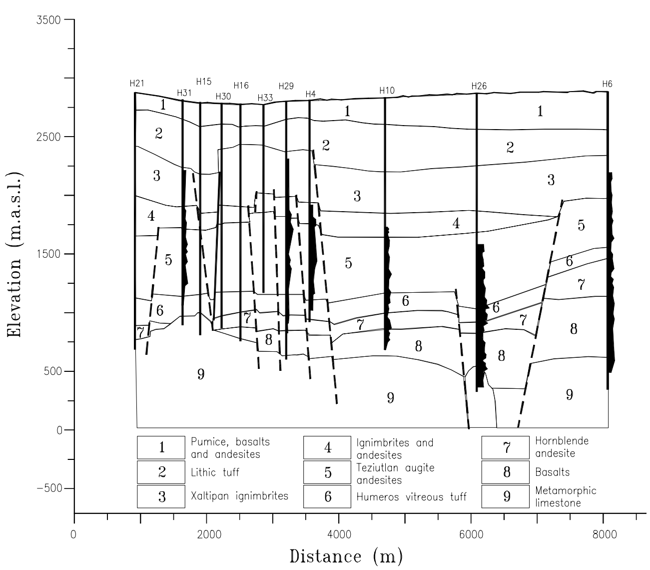

Figure 11.- Epidote distribution in geological section L3. Dark area represents the relative percentage of epidote

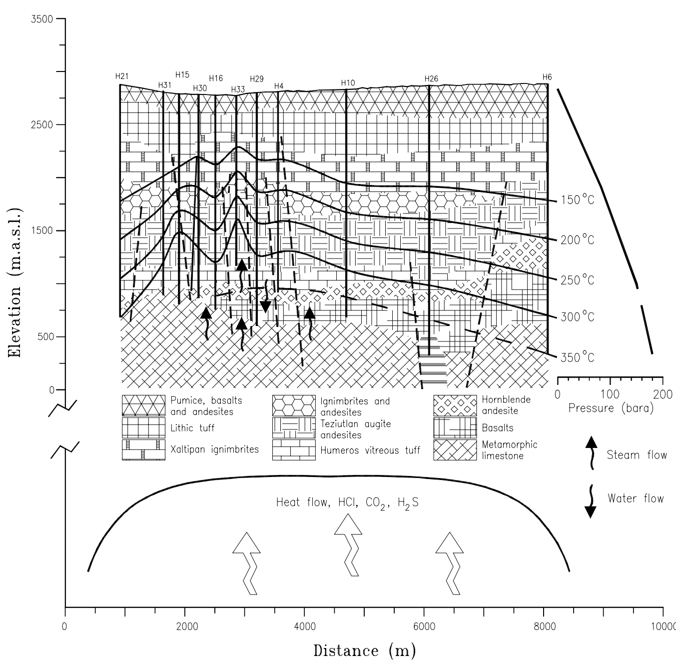

Figure 12.- Conceptual model of the Los Humeros geothermal field.