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Initial temperature field in the Los Humeros geothermal reservoir

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RESUMEN

Se presenta el campo de temperaturas iniciales o de formación del yacimiento geotérmico de Los Humeros. Se estimaron las temperaturas estabilizadas de las formaciones de los 40 pozos del campo usando los métodos de Horner y del Flujo de Calor Esférico Radial (SRF). Ambos juegos de temperaturas se compararon con las temperaturas de formación obtenidas mediante simulación numérica de los procesos de circulación y paro de los pozos. De las comparaciones, se seleccionaron las temperaturas de formación obtenidas por el método SRF como más realistas que las obtenidas por el método de Horner. En las simulaciones, la última serie de registros se reprodujo considerando pérdidas de circulación. Se incluye como ejemplo la simulación del pozo H-26. Se obtuvieron diferentes curvas isotérmicas de las temperaturas de yacimiento para los pozos en diferentes cortes geológicos seccionales y se incluyen tres secciones de este tipo: dos longitudinales y una transversal, las cuales ilustran la distribución de temperatura inicial del campo geotérmico. La distribución de temperatura inicial muestra las características térmicas y la relación entre anomalías térmicas y fallas del yacimiento.

PALABRAS CLAVE: Distribución de temperatura inicial, Los Humeros, método de Horner, método de Flujo de Calor Esférico Radial, simulación numérica.

ABSTRACT

The initial formation temperature field of the Los Humeros geothermal reservoir is presented. The stabilized formation temperatures were estimated for the 40 wells from this field using the Horner and the Spherical Radial Flow (SRF) methods. Both sets of formation temperatures were compared with the formation temperatures obtained by numerical simulation of the circulation and shut-in processes of the wells. From these comparisons, the formation temperatures obtained by the SRF method were chosen as more realistic than the Horner method temperatures. In the simulations, the last series of temperature logs was reproduced numerically considering circulation losses. Results for well H-26 are included as an example. Then isothermal curves of the formation temperatures for wells along different geological sections were obtained. Three sections are included, two longitudinal and one traverse, that illustrate the field initial temperature distribution. The observed temperature distribution shows the reservoir thermal features and the relationship of thermal anomalies and reservoir faults.

KEY WORDS: Initial temperature distribution, Los Humeros, Horner method, Spherical Radial Flow method, numerical simulation.

INTRODUCTION

The geological characteristics of the Los Humeros geothermal field have been described previously (Arellano *et al.*, 1998; 1999; 2000) while the origin of the acid fluids and the hydrothermal alteration were reported by Izquierdo *et al.* (2000). The Los Humeros geothermal field is located in the eastern part of the Mexican Volcanic Belt (19° 40' latitude N, 97° 25' longitude W), some 200 km from Mexico City (Figure 1). In 1982, the first deep well was drilled to confirm the results of previous studies. The commercial exploitation of the resource began in 1990 with the installation of the first 5MWe power plant. Presently, 40 wells have been drilled and the installed capacity totals 40MWe. The reservoir producing zones are located between -12 and 1610 m.a.s.l. Figure 2 shows the location of the wells (Barragán *et al.*, 2000a,b). In 1989, the original completion of some wells located in the Central Collapse zone was modified due to the occurrence of corrosion and plugging processes in the deep casings caused by acid fluids. Well H-1 located in the Maztaloya corridor was deviated due to pipe scaling. Most wells produce a high steam fraction at separation conditions and exhibit the excess steam phenomenon that makes difficult reconstruction of the fluid chemical composition at reservoir conditions. This fact also affects correct temperature estimation using geothermometers.

FLUID STATE AND INCONDENSABLE GASES

The geochemical characteristics of the produced fluids give evidence of at least two reservoirs. The shallower one is liquid dominated at 245°C and the deeper reservoir is vapor

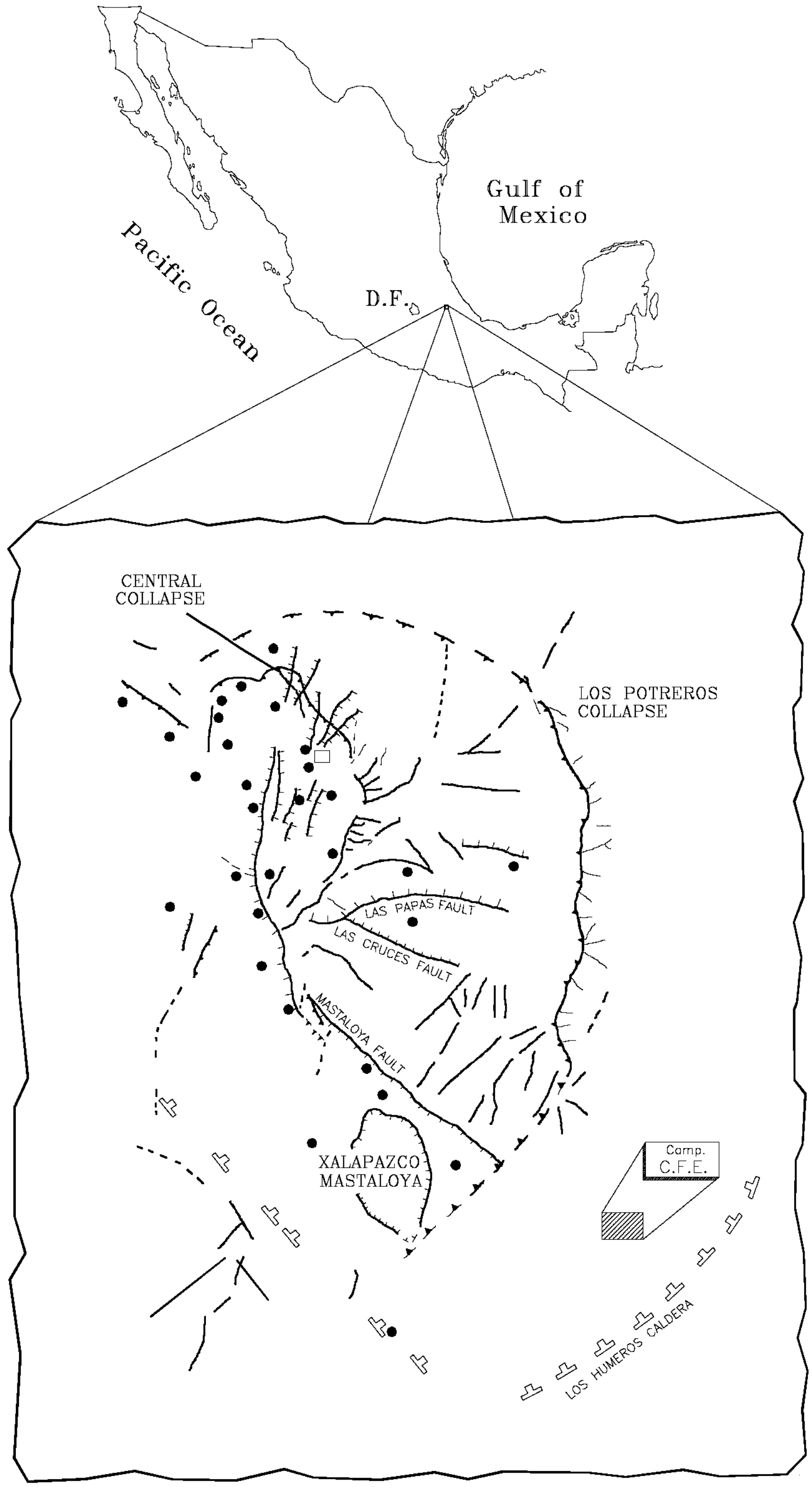

Fig. 1. Location of Los Humeros, Puebla, geothermal field.

dominated. At wellhead conditions, the wells produce a small amount of water except well H-1, which is fed from the shallow strata. Fluid classification is complex since they exhibit characteristics of a mixture and their classification varies with time. Evidence exists of the absence of water-rock total equilibrium and the reservoir temperatures obtained from cationic geothermometers are underestimated. The produced water is diluted in salt content and has a neutral pH at sepa-

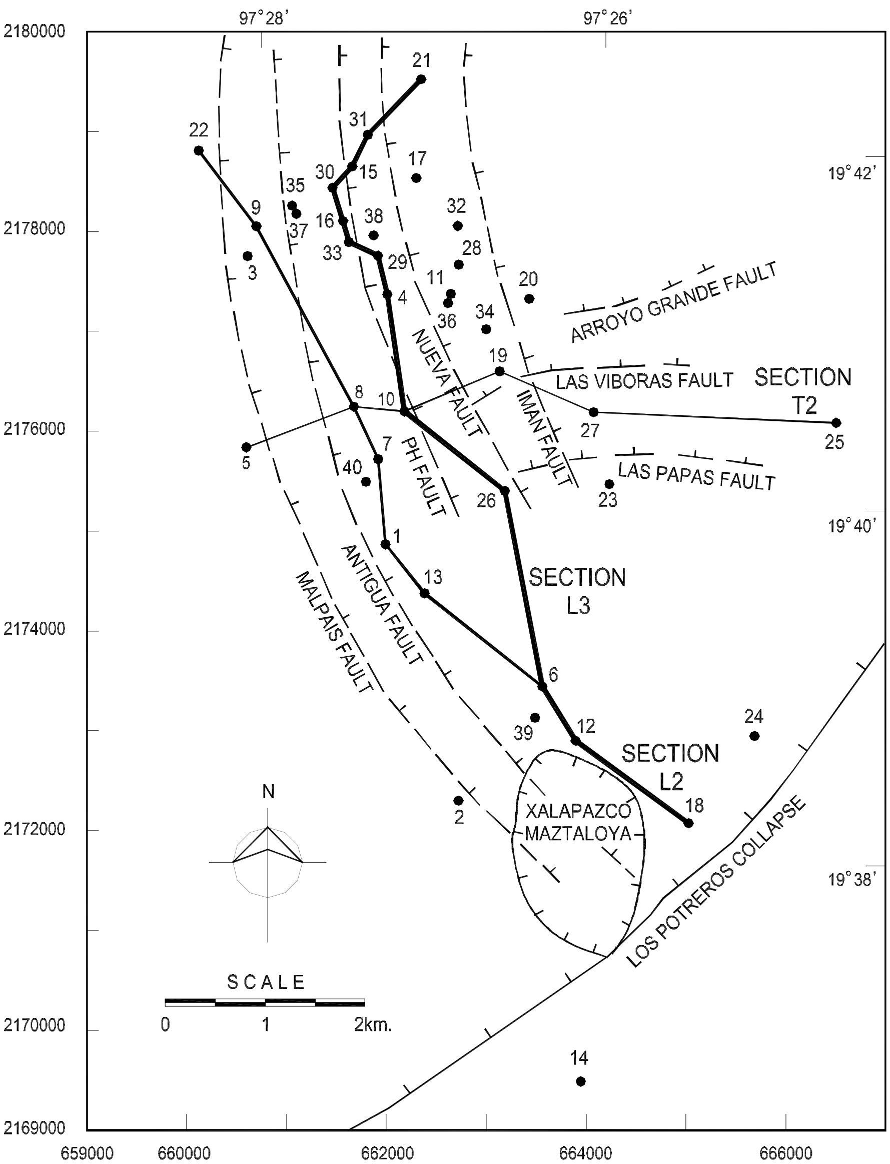

Fig. 2. Location of wells in Los Humeros, Puebla, geothermal field.

rator conditions, except for wells H-4 and H-16, located in the Central Corridor. These wells produced acid fluids that caused corrosion and plugging of well H-16 since it was fed from the two producing strata. Thus, well H-4 was abandoned and well H-16 was cemented at its deepest parts to be produced from the shallower strata only (Barragán *et al.*, 2000a,b, Arellano *et al.*, 1998). Analysis of the gas phase by a new method (D'Amore, 1998) allowed estimation of reservoir temperatures and the excess steam fraction present in the wells total discharge (Arellano *et al.*, 1998). The results showed that the natural-state reservoir temperature was between 275 and 337°C while the excess steam fraction was between 0 (for well H-1) and 1 (for wells H-9, H-12 and H-19). The same analysis was performed in 1997 (exploited reservoir) and the results indicated in general, a greater reservoir temperature above 300°C (except for well H-15 after repair), as well as the lowest excess steam fraction values (less than 0.3 except for well H-15 after repair). It was thus established the probable up-flow of hotter fluids through the fracture system. The incondensable gases vary widely in content along the field and reach 7% of the total gas when corrected at 8 bar in the southern part (Tovar and López, 1999).

STATIC FORMATION TEMPERATURES, SFTs

SFTs are normally estimated using temperature logs measured during drilling stoppages, after circulation stops as the well returns to thermal equilibrium. SFT estimation is mainly affected by (i) the duration of drilling fluid circulation, (ii) the nature of the heat transfer processes during drilling, and (iii) the drilling technology employed (Drury, 1984; Deming, 1989; Santoyo *et al*., 2000). The methods based on logged temperatures may be classified as line source, type-curve or trend analysis. The assumption of cylindrical radial heat flow in conductive formations is often used while convective heat transfer is present when circulation losses occur. The cylindrical geometry implies adiabatic boundaries, which is not always a realistic assumption and is one of the main reasons why unperturbed formation temperatures are underestimated. SFTs can also be estimated using numerical simulators which attempt to reproduce the thermal history of the drilling fluid column and the surrounding formation (Beirute, 1991; García *et al*., 1998). Two developments are worth. Takahashi *et al*. (1997) modified the GEOTEMP2 code to include circulation losses and validated their model using drilling outlet temperatures while García *et al*. (1996) developed the GEOTRANS simulator to include circulation losses and validated their results using temperature logs. The use of the GEOTRANS simulator is discussed below.

The most common method used to estimate static formation temperatures is the Horner method or Horner plot:

$$T_{ws} = T_i - m\log\left(\frac{t_c + \Delta t}{\Delta t}\right). \quad (1)$$

This model describes a straight line of slope m and the intercept Ti is the SFT, which is obtained by extrapolation to infinite shut-in time. The Horner method has been widely used in the geothermal industry, although it underestimates static formation temperatures (Ascencio *et al*., 1994). Practical considerations require that these temperatures be measured at the bottom of the hole where circulation times are on the order of a few hours such that the straight line is clearly defined (Dowdle and Cobb, 1975).

The SRF method is a more accurate and simpler method to estimate SFTs (Ascencio *et al*., 1994). It assumes a spherical-radial heat-conducting medium at the bottom of the well. A plot of shut-in temperature (Tws) versus the inverse of the squared root of shut-in time describes a straight line of slope m' and intercept or SFT, and does not require the circulation time explicitly. Its application criteria is described elsewhere (Ascencio *et al*., 1994; 1997). The SRF method is based on:

$$T_{ws} = T_i - m'\frac{1}{\sqrt{\Delta t}}. \quad (2)$$

This method has proven to give SFTs closer to the true formation temperatures (Hanano, 1996; Espinosa *et al*., 2001) and has been applied to oil wells with better results than the Horner method and comparable results to those of Hasan and Kabir (1994). Its use in geothermal wells proved very satisfactory when compared to the improved Horner method (Roux *et al*., 1980) and other methods (Hasan and Kabir, 1994).

In this work, the initial temperature distribution of the Los Humeros geothermal field is presented. The SFTs were obtained using the Horner and SRF methods and results of the latter method were found to be more representative of the true formation temperatures. Finally, the isotherms related to the natural-state temperature distribution of the Los Humeros reservoir were plotted in three geological sections.

SFT RESULTS

a) Horner and SRF methods

SFTs of 40 wells from Los Humeros geothermal field were obtained using the Horner and SRF methods. About 180 estimates were obtained with each method after considering all temperature logs obtained by stage testing (Grant *et al*., 1982; 1984) for each well. Significant differences of the results of each method were found and the SRF SFTs were always greater than the Horner method SFTs, as expected.

b) Numerical simulation of well H-26

Simulation was used to determine if an SFT profile based on either the Horner method or the SRF method allows reproduction of the logged temperatures in a well. Results of well H-26 are included as example. The simulation considers circulation losses and starts from an unperturbed assumed formation temperature profile. This profile is modified until the logged temperatures are reproduced iteratively. The last profile obtained is the best approximation to the reservoir temperature surrounding the well. Conceptually, it is the unperturbed formation temperature and should be close to the Horner or the SRF static formation temperature profile. This comparison represents an additional criterion about the representativity of the true formation temperatures predicted by the Horner or SRF methods inasmuch as the simulated temperature profile resembles more the SFT profiles obtained with either method. The simulations were performed using the GEOTRANS simulator (García *et al*., 1996; 1998; 2000) and the information required was obtained from the well drilling records.

Well H-26

Well H-26 was drilled with diameters of 26", 17-1/2, 12-1/4" and 8-1/2" at 43, 510, 2000 and 2546 m depths, respectively. The casings have 20", 13.375" and 9.625" diameters and run down to 42 503 and 1903 m, respectively. The 7" hanger is located at 1847 m while the liner extends to 2450 m. During the last drilling stage temperature logs T-28 through T-34 were run at 0,6,12,18,24,30 and 36 hr shut-in time to a depth of 2530 m. Temperatures above 340°C were recorded and partial circulation losses occurred between 10 and 2300 m in varying amounts and discontinuous form. The well traverses lithological units 1, 3, 5, 6 and 7 described by Arellano *et al*. (1999; 2000). The well shows two permeable zones, one between 2000 and 2200 m, and the other between 2400 m and total depth.

The maximum SFTs estimated with the Horner and SRF methods are 365°C and 407°C, respectively. Figure 3 shows temperature logs T-28, T30 and. Also plotted are the circulation losses and SFTs obtained with the Horner and SRF methods. It is seen that the temperature profiles are concave between 1900 and 2150 m due to circulation losses. The warm-up process is slower due to the cooling effect of flow into the formation during mud circulation, followed by a decreased formation thermal diffusivity during shut-in since the fluid that stays in the rock outside the well. Increase in the temperature gradient at about 2300 m suggests that the major loss zone is above 2300 m. A minor loss zone at about 2500 m is indicated by a cold zone. Faster heating between 2300 m and 2450 m shows that little or no fluid was lost here.

Reproduction of logged temperatures

Simulation starts by perturbing cooling the well by drilling fluid circulation. Then, circulation is stopped and the well and formation temperature distributions are recorded and this information is used the new initial condition for the warm-up process. During this period, temperature builds up and the logged temperatures are reproduced numerically with the well shut-in. If logged and simulated temperatures do not match, a new initial temperature profile is assumed before cooling the well and the process is repeated until convergence. This iterative process is complex and the presence of circulation fluid losses complicates the simulation since these become a new fitting parameter. With this information, a circulation period was simulated. Mud flow rate was 133 m^3/hr entering the well at 20°C and assuming a surface temperature of 25°C. Mud properties include: thermal conductivity of 0.7 W/m-K, a density of 1080 kg/m^3, a viscosity of 0.044 N-s/m^2 and a specific heat of 4100 J/kg-K. Circulation time was 2.5 hr. Figure 4 shows a complete picture of the information used for simulation of well H-26.

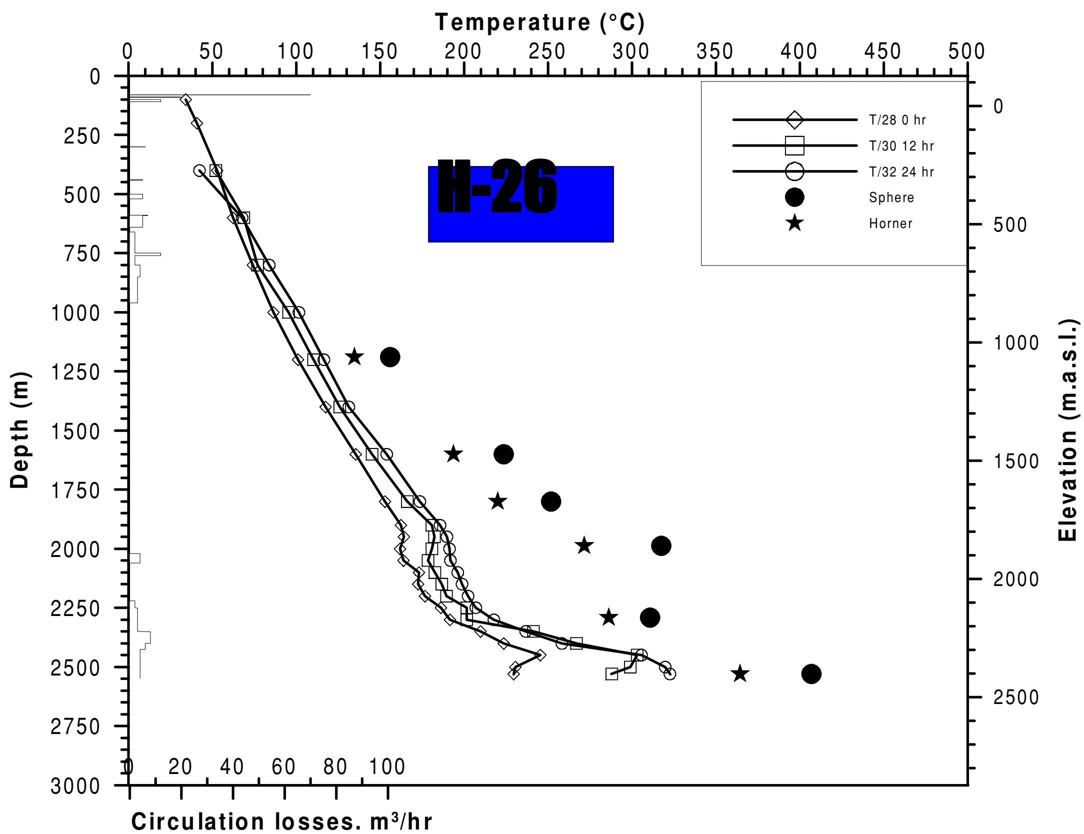

Fig. 3. Temperature logs T/28 - T/30 measured in well H-26. Also shown are the static formation temperatures estimated with the Horner and SRF methods.

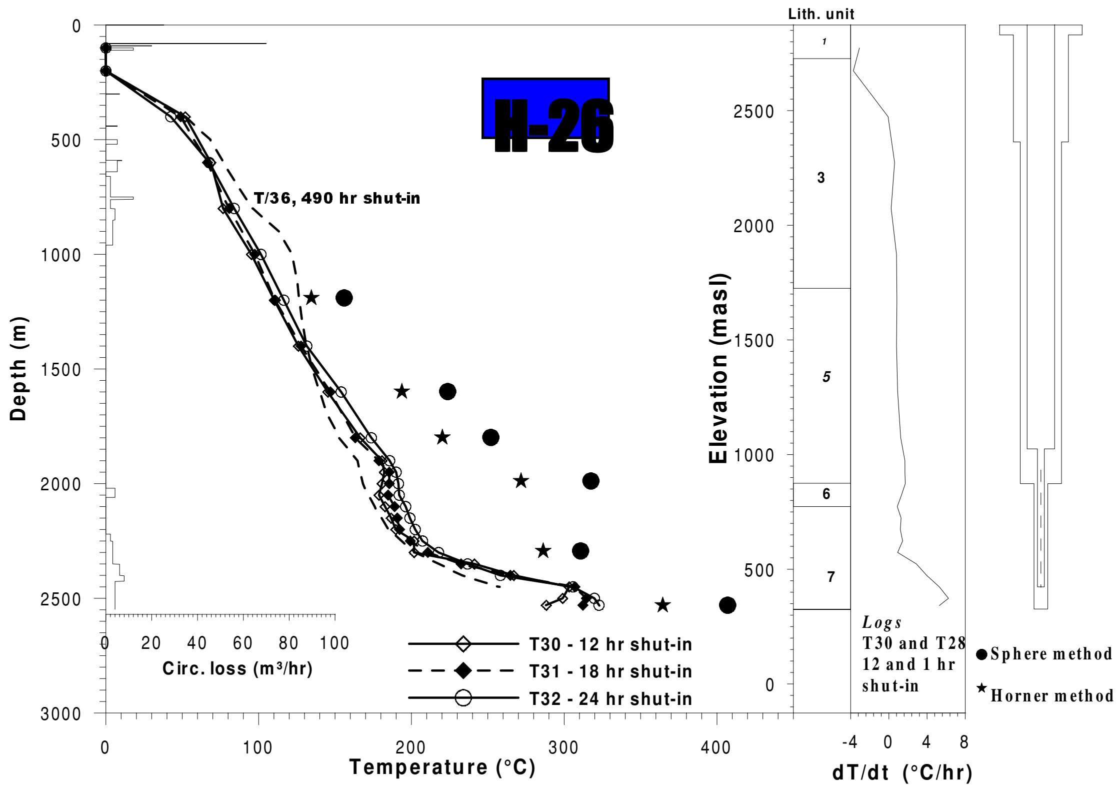

Fig. 4. Drilling fluid losses, temperature logs, static temperatures and lithology obtained during drilling and termination of well H-26.

The end of the circulation period is the beginning of the shut-in period. Log T-28 was run at the beginning of the shut-in period and during simulation, this log and other subsequent logs were reproduced numerically. Figure 5 shows a comparison of measured and computed temperature profiles at 0, 12 and 24 hr shut-in time. It is observed that the match is satisfactory at earlier shut-in times and that the computed profiles at 24 hr show a faster recovery in the zone of lost circulation, between 1900 and 2300 m. This may be due to the more intense heat transfer along the uncased part of the well, which caused a reduced heat transfer resistance (note that the 9-5/8"casing ends at 1903 m). Also, the effective thermal diffusivity of the formation invaded by drilling fluid was probably not well modeled. The continuous line to the right of Figure 5 is the temperature that the formation would have before perturbing the thermal field by well drilling. This profile is the result of the simulation of the combined circulation and shut-in period and was obtained after reproducing the logged profiles, Figure 5. Note that this temperature profile is closer to the SFTs obtained with the SRF method than those of the Horner method which supports the previous finding.

LOS HUMEROS INITIAL FORMATION TEMPERATURE

Figures 6 to 8 show the initial temperature distribution in Los Humeros geothermal reservoir along geological sections L2, L3 and T2. The 150, 200, 250, 300 and 350°C isotherms are displayed. They were constructed from the natural-state SFTs obtained by the SRF method for each well and then interpolating along each well to obtain the position of the temperature of each isotherm. Finally, the equal-temperature positions for each well were joined. It can be observed from Figure 6, Section L2 (NW-SE general direction), that higher temperatures are found at shallower levels in the northwestern part of the field (wells H22, H-9, H-8), reaching 200°C at about 1750 m.a.s.l. and 350°C at 800 m.a.s.l. near well H-8. The isotherms are found at deeper levels towards the southeastern parts and the 350°C curve is found below 0 m.a.s.l. near well H-18, towards the field boundary. The isotherms show peak temperatures near wells H-1, H-8 and H-9 and this appears to be related to an upward flow of hot fluid rising from greater depths along the faults and fractures near these wells. This ascent of hotter deeper fluid has also been observed from the field gas geochemistry (Barragán *et al*., 2000) and in the field pressure distribution (Arellano *et al*., 1998; 2000). However, around well H-7 the isotherms show a dip and this behavior was cross-checked from a similar analysis using information of the wells located along perpendicular sections to the that of the figure.

Figure 7 shows the temperature distribution in Section L3, with NNW-SSW general direction. Higher and

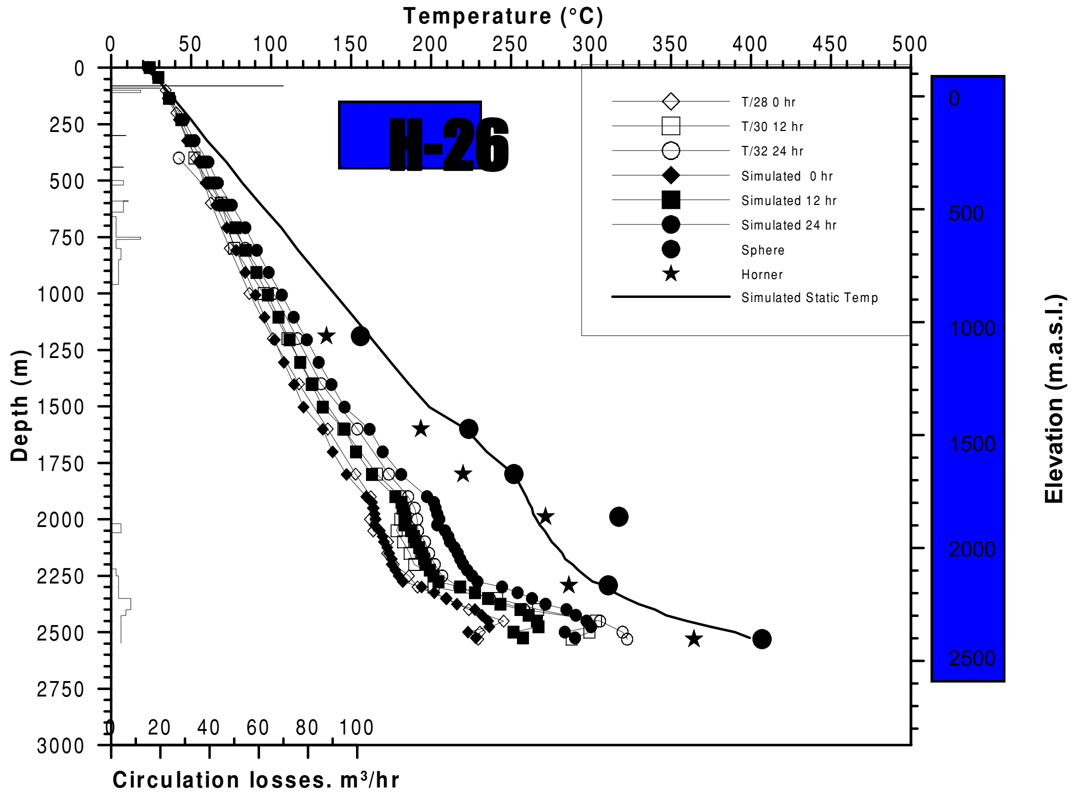

Fig. 5. Measured and computed temperature profiles in well H-26. Also shown are the static formation temperatures estimated with the Horner and SRM methods and the initial temperature profile of the formation.

shallower temperatures are found towards the NNW part of the field, between wells H-4 and H-15 and peaks near wells H-4, H-33 and H-30. Again, these peaks appear to be related to hotter ascending fluid from deeper levels through the field fractures and faults. The 350°C isotherm deepens to some 400 m.a.s.l. near well H-6. This is consistent with the location of the 350°C isotherm near well H-12, Figure 6, Section L2. A temperature dip is located near well H-16, between wells H-30 and H-33. This thermal behavior is similar to that observed from the pressure distribution in this part of the field (Arellano *et al*., 1998; 2000), where a dip is also observed along the isobaric curves. As in the preceding case, the temperature behavior was cross-checked by analyzing other sections perpendicular to Section L3. Figure 8 shows the temperature distribution in Section T2, with W-E general direction. Higher temperatures are found at shallower depths towards the west of the field, with peaking temperatures near well H-8. Hotter fluid appears to ascend through the faults and fractures located near wells H-10, H-8 and H-5. The corresponding pressure distribution also peaks near well H-10 (Arellano *et al*., 1998; 2000). It thus appears that higher temperatures are located at shallower depths in the northwestern (upper left quadrant in Figure 2) of the field and that hot fluid ascends through fault and fractures from deeper levels.

CONCLUSIONS

Static reservoir temperatures were estimated for 40 wells form the Los Humeros geothermal field by the Horner and SRF methods. The Horner method underestimates formation temperatures while the SRF method gives temperatures that are closer to the true formation temperatures. This was supported by numerical simulation of a combined circulation and shut-in period in several wells, and results for well H-26 were presented. Numerical reproduction of logged temperatures is more feasible if an initial temperature profile based on the SRF method is employed instead of using an initial temperature profile based on the Horner method. Finally, the temperature distribution plotted in three geological sections and the pressure distribution analysis show the parts of the reservoir where hot fluid ascends in the reservoir.

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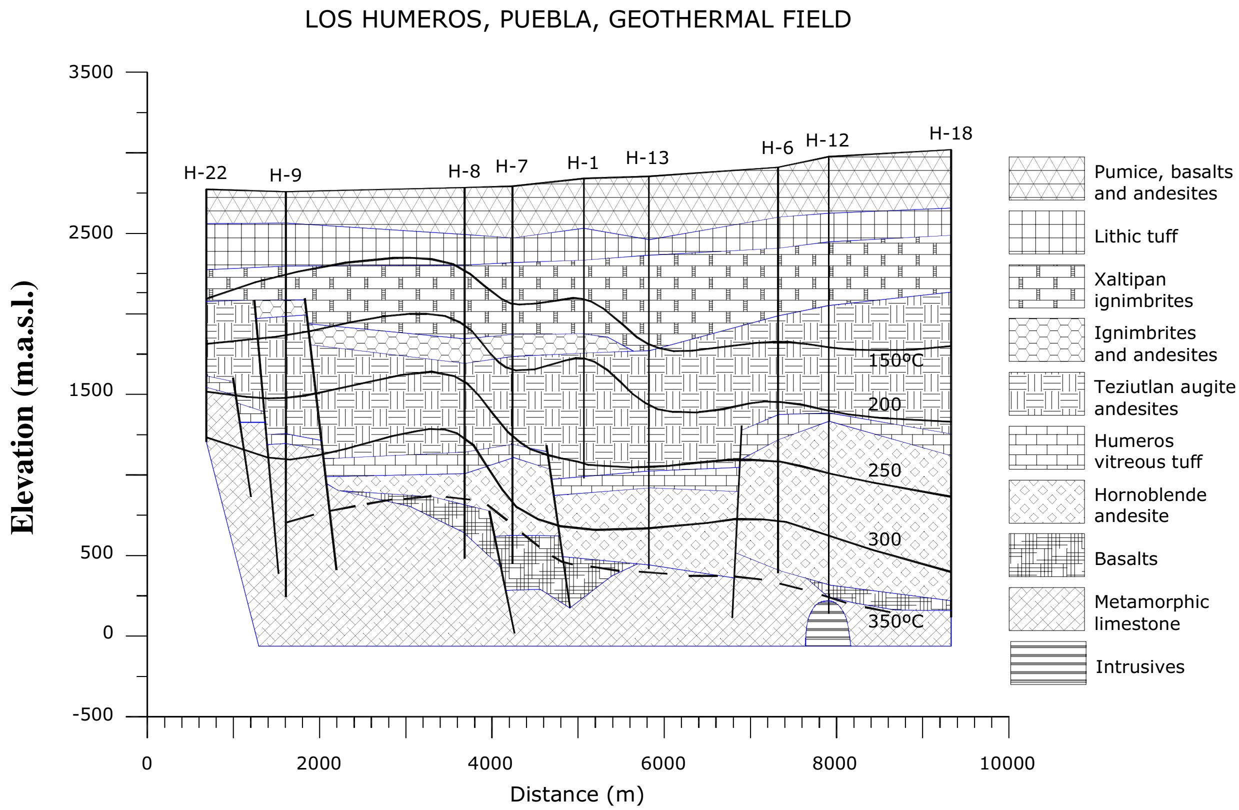

Fig. 6. Los Humeros geothermal field initial temperature distribution in geological section L2 (NW-SE general direction).

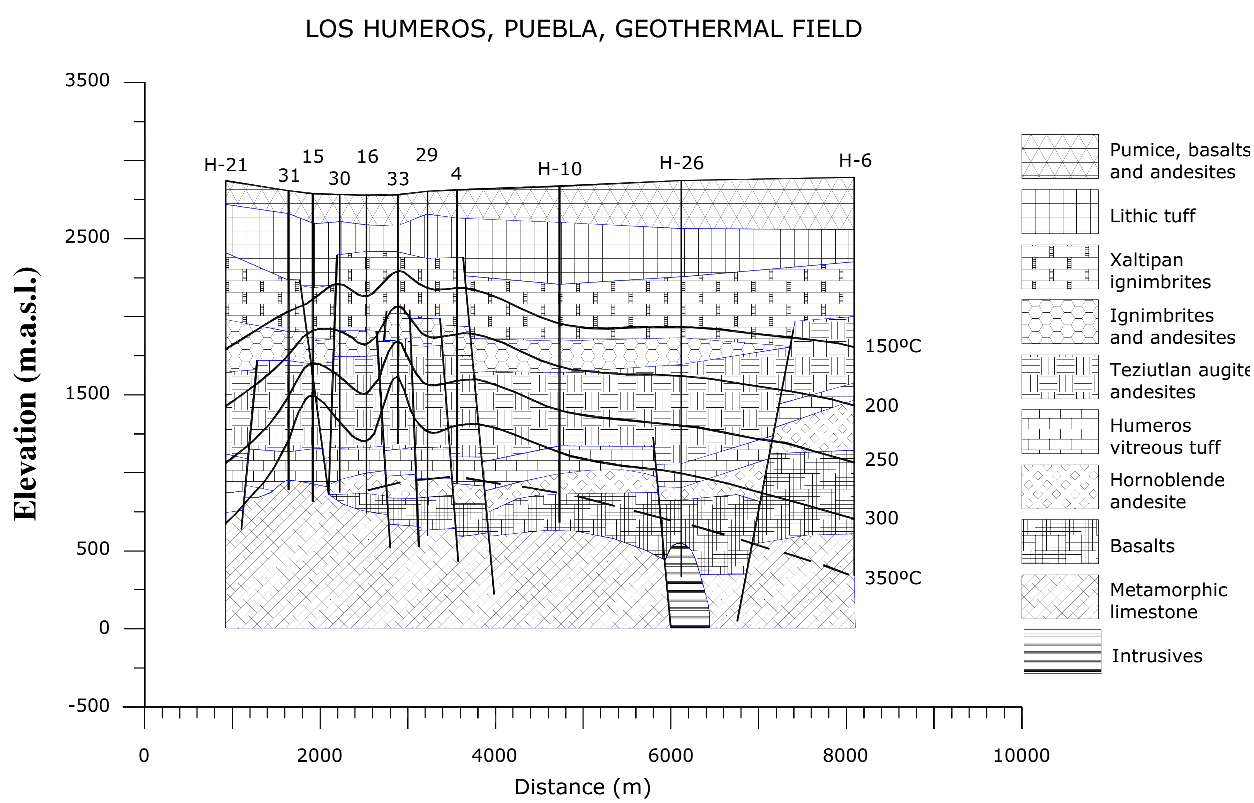

Fig. 7. Los Humeros geothermal field initial temperature distribution in geological section L3 (NNW-SSE general direction).

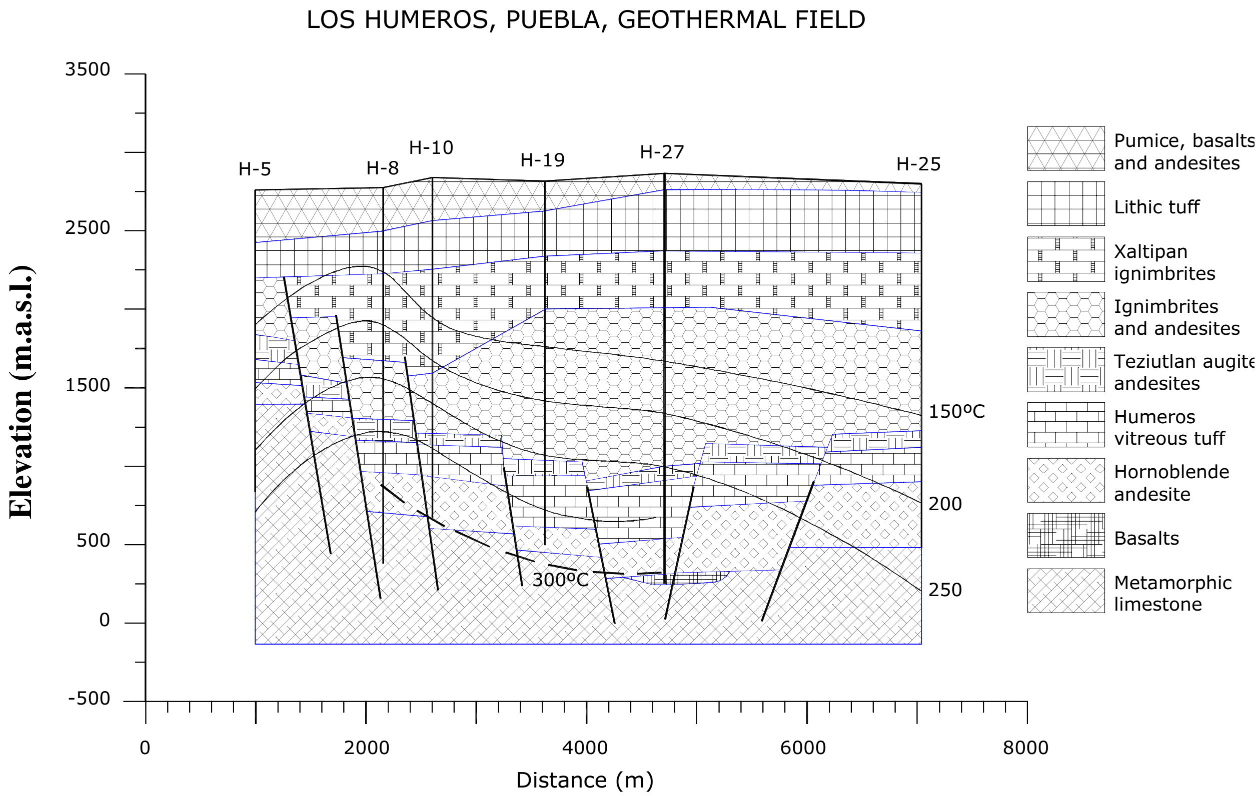

Fig. 8. Los Humeros geothermal field initial temperature distribution in geological section T2 (W-E general direction).

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