Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

THERMAL EVOLUTION STUDY OF THE LV-3 WELL IN THE TRES VIRGENES GEOTHERMAL FIELD, MEXICO

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Key Words: lost circulation, drilling, shut-in, static formation temperature, Las Tres Virgenes geothermal system

ABSTRACT

A thermal evolution study of the LV-3 geothermal well (depth: 2150 m) is presented. Such a study is based on wellbore temperature logs, transient temperature profiles (obtained from numerical modeling of the heat transfer processes during well drilling and shut-in) and fluid inclusion logging. Drilling and shut-in temperature profiles were predicted by use of a transient wellbore thermal simulator which considers conductive and convective heat transfer processes. Such a numerical simulation considered the LV-3 well geometry in the presence of fluid losses into the formation. Thus, numerical simulation enabled the drilling and shut-in thermal history of well LV-3 to be closely reproduced. Precision temperature logs from LV-3 well (at 402-m and 2000-m) provided information on the location of permeable zones intersecting the wellbore. Such permeable zones were partially identified at a wellbore depth of 400-m and more significantly between 1300-m and 1600-m.

Microthermometric determinations on well cuttings and core samples containing veins filled with secondary minerals (epidote, quartz and calcite) were also carried out. Minimum homogenization temperatures ranging from 109 °C to 125 °C were measured in the first 920 m deep. Between 1830 m and 2150 m deep, the minimum homogenization temperatures ranged from 256 °C to 268 °C. Likewise salinity concentration ranges from 3.4 to 18.5 wt% as NaCl equivalent were found. Static formation temperatures were also computed by five analytical methods which are the most commonly used in the geothermal industry: the classical Horner plot, the improved Horner, the two-point method and the spherical-radial and cylindrical-radial heat flow models. A comparison among the wellbore temperature logs, the homogenization temperatures, and the transient temperature profiles is also presented.

1. INTRODUCTION

Las Tres Virgenes (LTV) geothermal field is located in the eastern coast of the Baja California Peninsula, 35 km NW of Santa Rosalía city (Fig.1). The Comisión Federal de Electricidad (CFE) started geothermal exploration activities here since the 1980s. Numerous geothermal surveys of geology, geochemistry and geophysics have been carried out (e.g. Ballina and Herrera; 1984; Lira et al., 1984; Quijano, 1984; Tello, 1988; Gutiérrez-Negrín, 1990; Viggiano, 1992; López-Hernández et al., 1995; Tello, 1997). Such studies have been conducted to obtain a better knowledge of the natural state of the geothermal system.

To date, six wells have been drilled. Four of them are producing wells and the others are used as injection wells (Tello, 1997). Figure 2 presents a simplified geological map showing the location of the wells drilled in LTV. At present, information derived from the completion activities of these boreholes is being used to define the reservoir size and its thermal structure. In this sense, such information can be used for determining both the undisturbed formation temperature and the geothermal gradient of the site as well as for identifying the permeable or productng horizons of the reservoir.

Having these last objectives in mind, the LV-3 well drilling and shut-in history as well as its temperature measurements have been selected for studying its thermal evolution. LV-3 well was selected since it had several lost circulation problems which were reported in detail. The availability of this information enables the permeable zones of the geothermal reservoir to be identified as well as the effect of the heat transfer processes on the transient temperature profiles to be analyzed. The main objective of this paper is to present a study of the thermal evolution of the LV-3 well based on: (a) wellbore temperature logs; (b) fluid inclusion logging; (c) transient numerical modeling of the heat transfer processes that governed the geothermal well drilling and shut-in operations and (d) static formation temperatures calculated by use of analytical methods.

2. GEOLOGICAL SETTING

Within a regional context, the geothermal system of LTV is located in a Plio-Quaternary depression of NW-SE trend, the Santa Rosalía basin which constitutes the western limit of a deformation zone related to the Gulf of California opening (Demant, 1981; López-Hernández et al., 1995). The western border of the basin is occupied by a faults system trending NW-SE. Gutierrez-Negrín (1990) and Viggiano (1992) established that LTV is located in an active tectonically area associated with the faulting process of the Gulf of California opening. Three Quaternary volcanic centers (from oldest to the youngest): La Reforma caldera, the Sierra Aguajito and Las Tres Virgenes complex (LTVC) were identified. The chemical compositions of these volcanic complexes are characterized by calco-alkaline series, excepting an alkaline rich pyroclastic flow and some basaltic cones observed at La Reforma, which are of peralkaline type (Sawlan, 1986).

The most active thermal zone has been located in the northern limit of the youngest volcanic center (LTVC) whose age is around 0.44 Ma. This complex comprises of three volcanoes: La Virgen, El Azufre and El Viejo. In the north zone of LTVC, a chemical composition of dacitic type was observed. The south zone shows a different chemical composition covering a range from basaltic to rhyolitic products.

Regional and local geological maps of the LTV geothermal system have already been published (e.g. see Figs. 1-3: López-Hernández et al., 1995). A complete compilation of the main geological and geophysical features of LTV is also reported by López-Hernández et al. (1995). Geochemical studies for determining the chemical and isotopic composition of geothermal fluids including its classification and the equilibrium state were carried out by Tello (1997).

Fluids geothermometry based on the chemical analyses reported by Tello (1997) and by use of the Na/K geothermometer (Verma and Santoyo, 1997) indicate underground temperatures for LV-1, LV-3, LV-4 and LV-5 of 263 ± 25°C, 263 ± 25°C, 269 ± 26°C and 263 ± 25°C, respectively.

3. DRILLING HISTORY OF WELL LV-3

Well LV-3 was drilled in the Las Tres Virgenes geothermal field. Wellbore geometry is shown in Fig. 3. It is 2150 m deep and was completed in November 1994 (De Leon-Vivar, 1996). Hole diameters are 26, 17 ½, 12 ¼, and 8 ½ in. Casing diameters are 20, 13 3/8 and 9 5/8 in. The production liner has a diameter of 7 in and runs from about 1260 m to 2133 m.

Primary lithology of LV-3 is characterized by a column consisting of four main sections: a dacites zone (38-160 m); an andesites zone called Santa Lucía formation (160-650 m); a sandstone zone known as Comondú group formation (650-899 m); and a granite zone (900-2150 m): De Leon-Vivar, 1996.

4. TEMPERATURE BUILD-UP DATA

Several series of temperature logs were run during the LV-3 drilling and shut-in operations (De Leon-Vivar, 1996). The temperature build-up tests were limited to short shut-in times (up to 24 hours) for reducing the global well drilling costs. The first series was logged when the well drilling was stopped at 402 m deep. The 20 in casing section was cemented to 48 m while the 17 ½ in was completed to 402 m. At this wellbore depth, four temperatures profiles were logged (logs T-1, T-3, T-4 and T-5; Fig. 4).

A preliminary analysis of the log T-1 indicates a nearly isothermal temperature profile in a depth range from 200 m to 380 m. A conductive heating process is clearly evidenced at long shut-in times, when the well depth was greater than 150 m. The temperature gradient of the well between 150 m and 400 m is about 8 °C/100 m (log T-5). At this well depth, small fluid losses were reported.

The fifth series was carried out when the well attained a depth of 2000 m near the end of its completion (2150 m). Logs T-26 to T-30 were recorded (Fig. 5). Such measurements were logged between 300 and nearly 2000 m after 0, 6, 12, 18 and 24 hours of shut-in time.

Although, the analysis of these logs is a more complex task due to the anomalous shape of temperature profiles, some evidences on the heat transfer processes can be pointed out. A more intensive conductive heating rate is exhibited between 300 m and 1300 m, where the temperature gradient indicated an approximated value of 12 °C/100 m (log T-30). Below this depth, higher circulation losses occurred (between 1300 m and 1650 m). At this zone, convective heat transfer processes due to fluid losses governed the shape of the temperature profiles. Immediately below 1650 m, a very slow heating rate was observed.

5. STATIC FORMATION TEMPERATURE

The analysis of temperature logs has been traditionally used for calculating static formation temperatures (SFTs). Such estimations are usually made by extrapolating analytical methods: e.g. Horner plot (Dowdle and Cobb, 1975), the improved Horner (Roux et al., 1979); the two-point model (Kritikos and Kutasov, 1988); the spherical-radial model (Ascencio et al., 1994) or the cylindrical-source heat flow model (Hasan and Kabir, 1994). Historically, it has been demonstrated that temperature logs provide only isolated data of the true formation temperature (TFT) and that SFT estimations inferred from these extrapolations are always less than the TFT (Luhesi, 1983; Shen and Beck, 1986; Santoyo; 1997; Santoyo et al., 1999).

A more reliable estimation of the equilibrium or TFT should require a complete and careful analysis of the thermal history of the well under circulating and shut-in conditions as well as a subsequent comparison with temperature estimations obtained by alternative methods, such as: (i) fluid inclusion logging or microthermometric techniques (Ikeuchi et al., 1996; González-Partida et al., 1997); (ii) numerical modeling of the heat transfer processes that govern the drilling and shut-in of a well (Beirute, 1991; Santoyo; 1997; Takahashi et al., 1997; García et al., 1998a, 1998b); (iii) fluid geothermometry (Verma and Santoyo, 1997); or (iv) calibrated melting tablets (Sawaki, et al., 1997). In the following section, a comparative study based on tools (i) and (ii) is outlined.

Analytical methods. SFTs have been estimated by use of the two series of temperature logs. Five analytical methods were used for inferring the SFT values: (i) the traditional Horner plot; (ii) the improved Horner plot recommended by Roux et al., 1979; (iii) the two-point method suggested by Kritikos and Kutasov, 1988; (iv) the spherical-radial heat flow (SRHF) model proposed by Ascencio et al., (1994); and (v) the rigorous solution of the cylindrical-source heat flow (CSHF) model proposed by Hasan and Kabir, (1994). The numerical algorithms of these methods were included in the computer code STATIC_TEMP which was developed for calculating SFTs in geothermal wells (Santoyo et al., 1999).

After analyzing the first series of temperature logs (T-1, T-3, T-4 and T-5), the estimated SFT by such methods was determined to be 66°C, 72.8°C, 78.2°C, 75.5°C and 69.5°C, respectively. The average value of these estimates is around 72.4°C. All the SFTs estimated could include uncertainties up to several degrees Celsius. To date, a correct knowledge of these uncertainties or an appropriate methodology to evaluate them is still unknown or scarcely reported. Thus, an approximation of these uncertainties could be simply represented by the standard deviation (σ) of the above estimations (± 4.8°C). A more suitable method for calculating the uncertainties in each one of the analytical methods should use the error propagation theory (Bevington, 1969; Drury, 1984; Verma and Santoyo, 1997).

On the other hand, the analysis of the fifth series of temperature logs (T-26, T-27, T-28, T-29 and T-30) enabled the SFT at the wellbore depth of 2000 m to be determined. In this case, the estimated SFT values were 238.3 °C, 239.4 °C, 239.9 °C, 240.1 °C and 238.8 °C, respectively for the same analytical methods used. The average and standard deviation values of these SFT estimations are 239.3°C ± 0.8 °C.

Fluid inclusion studies. Microthermometric measurements were carried out on well cuttings and core samples containing veins filled with secondary minerals (epidote, quartz and calcite). Core slices and cuttings were doubly polished. The microthermometric measurements were performed on a Chaix-Meca heating-cooling stage, calibrated with melting points of various standards analytical reagents. From the observation of each fluid inclusion sample, three parameters were determined: (i) negative ice melting temperatures for estimating fluid salinity in terms of weight percent of NaCl; (ii) the homogenization temperatures (Th) for calculating the minimum formation temperature of the minerals studied; and (iii) positive clatharate fusion temperatures. Further details on the analytical techniques have been previously described by González-Partida et al., (1997).

Alteration minerals (epidote, quartz and calcite) collected between 570 to 2150 m depth were analyzed. Table 1 summarizes the information obtained at different depths of LV-3 well. Most of the measured fluid inclusions consisted of liquid and vapor mixture (L+V) with the liquid phase predominating. The size of the fluid inclusions ranged from 5 to 10 microns.

Minimum homogenization temperatures range from 109 °C (at 570 m) to 125 °C (at 920 m) while at the deepest zone of the well (1830-2150 m), these homogenization temperatures range from 256 °C to 268 °C. The microthermometric analyses showed the presence of a geothermal fluid with a variable salinity and associated with the early boiling stages of the geothermal system. At a well depth of 1202 m, the geothermal fluid exhibited a moderate salinity (8.95 wt% NaCl equivalent) with melting points ranging from -6 to –12.3 °C. Below this depth, between 1647 and 1830 m, a high salinity geothermal fluid (17.6 to 18.5 wt% NaCl equivalent) was found. A low salinity geothermal fluid (3.4 wt% NaCl equivalent) was detected at 1940 m deep. Finally, at a wellbore depth of 2000 m, the salinity of the geothermal fluid again increase up to 19.2 wt%.

Numerical modeling studies. Transient circulating and shut-in temperatures in and around well LV-3, in the presence of lost circulation were also determined. Such temperatures were calculated by use of a wellbore thermal simulator developed for accounting the transient convective heat transfer due to fluid losses (García et al., 1998a and 1999). These numerical studies used the two series of temperature logs for fixing an initial temperature profile of the site. Additional input data such as the wellbore geometry corresponding to each one of these series, the mud flowrate, the lost circulation history and the transport and thermophysical properties of the whole well drilling system (drill pipe, drilling materials, casing cement and formation) were also required.

The reliability of these simulation runs was confirmed when the measured temperature profiles were satisfactorily reproduced. Figure 6 shows a comparison of simulated and logged temperatures profiles for shut-in times of 0, 6, 12 and 18 hours and at 400 m deep. An acceptable agreement between the simulated and logged temperatures is observed, except for the log T-3 (shut-in time: 6 hrs) where small differences (less than 4 °C) were obtained. However, these differences disappeared as thermal recovery time proceeded.

Figure 7 shows the numerical results corresponding to a wellbore depth of 2000 m. A comparison between the simulated and the logged temperature profiles is again shown. In this case the effect of the lost circulation on the shape of the temperature profiles is clearly seen, particularly at depths of 1281, 1460, 1571 and 1685 m. This effect was due to the higher drilling losses which occurred in the well (approx. a 30 % of the total drilling fluid flowing into the well; De Leon-Vivar, 1996). Figure 7 also demonstrates that the temperature profile of the lost circulation region can be satisfactorily reproduced only if the convective heat flow process related to fluid losses into the formation is appropriately modeled. These results are important because it is well known that a matching procedure between logged and simulated temperatures under these drilling conditions, constitute a very complex task that can not be easily obtained by generic simulators. Most of the commercial wellbore thermal simulators use wholly conductive heat flow models, which generally neglect the effect of the fluid losses on the determination of temperatures in and around a wellbore (e.g. Wooley, 1980; Beirute, 1991; García et al., 1998b). In fact, there is a quite limited number of available simulators that consider the presence of the fluid losses (Santoyo, 1997; Takahashi et al., 1997; García et al., 1998a; García et al., 1999).

6. DISCUSSION

A compilation of the main results obtained in these thermal studies is presented in Fig. 8. Measured temperature profiles logged at the beginning of the thermal recovery process of the well (log T-26: 0 hrs of shut-in) and after 24 hours of shut-in (log T-30) are shown. Figure 8 also shows the minimum fluid inclusion temperatures and the SFTs calculated by means of the Horner and the SRHF methods. The initial formation temperature profile assumed in the numerical modeling runs and the sea level have been also included in Fig. 8.

It can be observed that the SFT predictions made by use of the classical Horner method were always less than the temperatures provided by the SRHF method. However, the minimum homogenization temperatures measured in the well show an acceptable agreement with SFTs inferred by SRHF method. Differences less than 12.6 % were obtained. In the majority of the cases analyzed, the minimum fluid inclusion temperatures provided the highest formation temperatures, except for the 900 m depth, where the SRHF method predicts the highest SFT value. Nevertheless, a measurement error in the fluid inclusion analysis could have been responsible for this low homogenization temperature. On the basis of this thermal behavior and since the fluid inclusion temperatures were normally higher than stabilized ones (SFTs-SRHF method), it demonstrates that the LV-3 well experienced a cooling process (González-Partida, 1997).

Regarding the numerical modeling results, it can be observed that the initial formation temperature profile assumed shows a good agreement with the minimum homogenization temperatures. Differences less than 3.5 % were observed, except for the 900 m deep where measurement errors possibly occurred. Thus, the analysis of these data enables the undisturbed formation temperature profile to be indirectly inferred.

The integration of all these results suggest the existence of a thermal structure consisting of three main layers. The first layer is a conductive heat flow zone (0-1200 m) characterized by a geothermal gradient of approx. 16.6 °C/100 m. The second layer is the permeable or producing zone of the well (1200-1650 m) where convective heat flow processes due to fluid losses governed the temperature profile shapes. Finally, the third layer is a conductive zone (1650-2150 m) where a slow conductive heating rate was exhibited during shut-in conditions with a geothermal gradient about 12 °C/100 m.

CONCLUSIONS

A thermal evolution study of the LV-3 well of Las Tres Virgenes geothermal field was carried out. Actual LV-3 temperature logs have been used. Static formation temperatures estimated by the SRHF method (Ascencio et al., 1994) provided the highest SFT values. At the deepest zone of the well, SRHF and the fluid inclusion logging temperatures indicated SFT values of 240.1 °C and 261 °C, respectively.

The numerical modeling of the drilling and shut-in history enabled the actual temperature logs in and around the well to be properly reproduced. Such a simulation included the study of the effect of the fluid losses on the circulating and shut-in temperature profiles.

The LV-3 initial formation temperature profile (assumed at the beginning of the numerical runs) was indirectly inferred when a comparison between the numerical modeling results of the well drilling and shut-in history and the homogenization temperature measurements was performed.

The analysis and the integration of all these studies suggested the existence of a thermal structure of LV-3 well consisting of three main layers: (i) a shallow conductive heat flow zone between 0 and 1200 m; (ii) a convective heat flow zone (1200-1650 m) where higher fluid losses occurred; and (iii) a deep conductive heat flow zone where a slow heating rate was exhibited during the thermal recovery of the well. With respect to this, the presence of the convective heat flow zone enabled the most permeable or producing zone of the well to be identified.

Even though the preliminary thermal structure of the LV-3 well has been deduced, additional research using information from other wells must be done to define the entire thermal structure of the reservoir. These activities would enable an accurate knowledge of the isotherms of the field to be completely defined.

ACKNOWLEDGMENTS

Thanks are due to the Comisión Federal de Electricidad (CFE) for providing useful information about the current drilling practices in the area of research.This work was initiated when the first author was working at the Instituto de Investigaciones Eléctricas. Partial support from PAPIIT (UNAM) project IN119798 is also acknowledged.

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Table 1. Summary of results of microthermometric measurements on fluid inclusions from drill cuttings and core samples from well LV-3, Las Tres Virgenes geothermal field, México.

Depth (m)	Host	Th range (°C)	Th_A (°C) (n)	T_{mi} range (°C)	$T_{mi\text{-}A}$ (°C) (n)	Salinity (% NaCl)$_{wt}$
570	Ca	109-109	109 (5)	-	-	-
580	Ca	114-127	118 (6)	+0.4 to +2.2	+1 (6)	n.c.
920	Qz	125-126	125.5 (10)	+0.4 to +2.2	-	-
1202	Qz	226-237	230 (23)	-6 to –12.3	-5.8 (23)	8.95
1202	Ep	227-264	241 (25)	-	-	-
1647	Qz	231-235	232 (27)	-14.9 to –14.9	-14.9 (27)	18.5
1830	Qz	256-271	261 (18)	-13.9 to –13.9	-13.9 (18)	17.6
1940	Qz	242-259	247 (9)	-2 to -2	-2 (9)	3.4
1940	Ep	237-259	243 (10)	-2 to -2	-2 (10)	3.4
2000	Ca	261-281	268 (21)	-15.7 to –15.7	-15.7 (10)	19.2
2150	Ca	261-263	261 (12)	-	-	-

Ca: calcite; Qz: quartz; Ep: epidote; Tmi: ice-melting temperature; Th: homogenization temperature; A: average; n: number of samples analyzed; n.c.: not calculated.

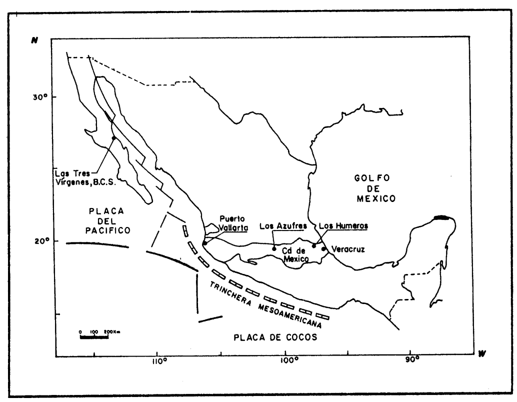

Fig. 1 Location of Las Tres Virgenes geothermal field, México

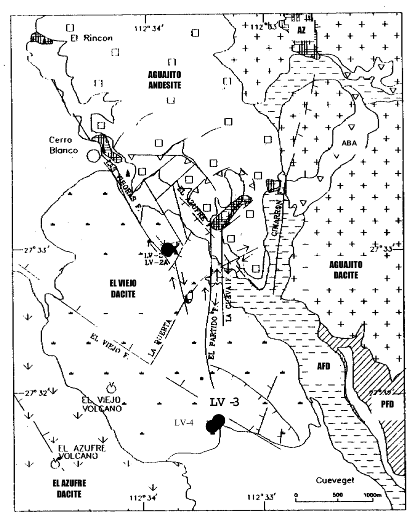

Fig. 2 Simplified geological map showing the location of LV-3 well drilled in Las Tres Virgenes geothermal field, México (modified after López-Hernández et al., 1995). AZ: alteration zone; AFD: alluvial fan deposits; PFD: pyroclastic flow deposits.

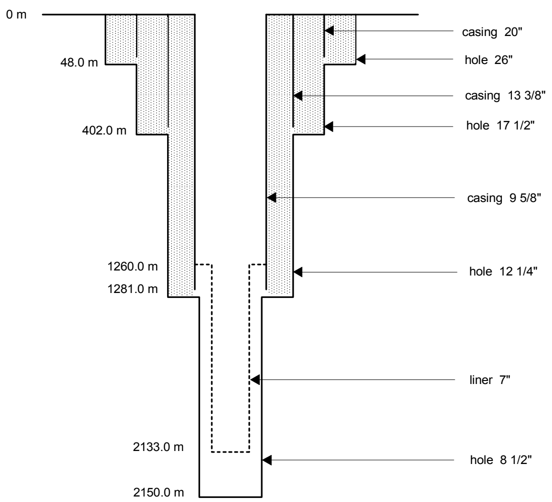

Fig. 3 Final completion geometry of LV-3 wellbore from Las Tres Virgenes geothermal field, México.

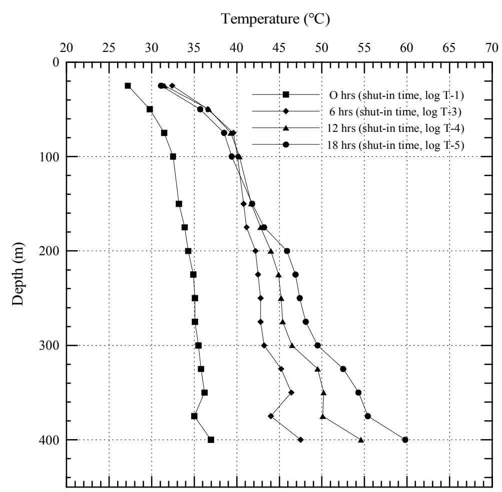

Fig. 4 Thermal behavior exhibited during the first drilling stage of well LV-3 at 400 m deep.

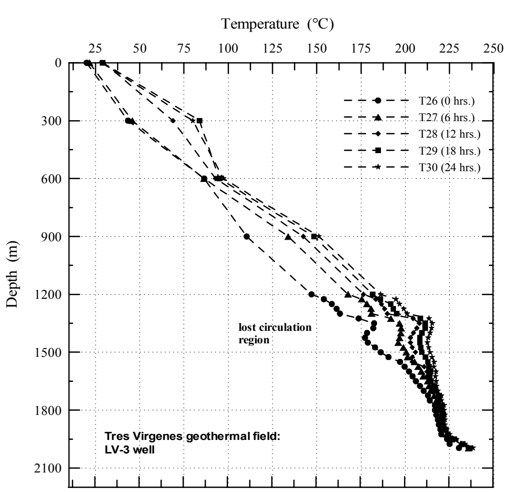

Fig. 5 Thermal behavior exhibited during the final drilling stage of well LV-3 at 2150 m deep.

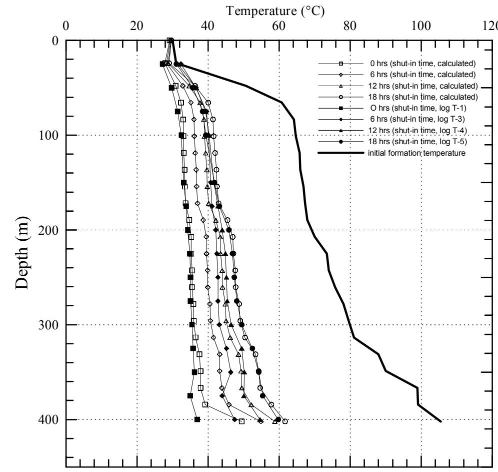

Fig. 6 Simulated and logged temperatures profiles in well LV-3 (at 400 m), Las Tres Virgenes Geothermal field.

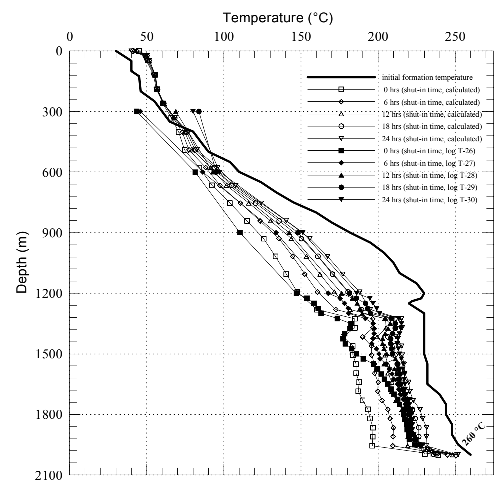

Fig. 7 Simulated and logged temperatures profiles in well LV-3 (at 2000 m, Las Tres Virgenes Geothermal field.

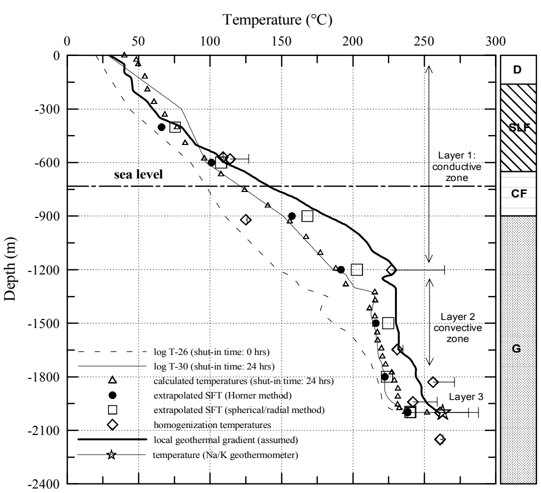

Fig. 8 Temperatures profiles in LV-3 well obtained from temperature logs, fluid inclusion analyses, numerical modeling of heat transfer processes and estimated SFTs by extrapolated analytical methods. The lithology of the well is also include at the right. D: dacite; SLF: Santa Lucía formation; the black square represents the Comondú formation group; G is the granite section.