NUMERICAL TOOL TO ESTIMATE THE GEOTHERMAL POTENTIAL FROM PETROLEUM AND GEOTHERMAL MEXICAN FIELDS

Orlando Miguel Espinoza-Ojeda[1], Elizabeth Rivera Calderón[2] & Víctor Hugo Garduño-Monroy[3]

[1] CONACyT - Instituto de Investigaciones en Ciencias de la Tierra, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, México – Centro Mexicano de Innovación en Energía Geotérmica.

[2] Posgrado - Instituto de Investigaciones en Ciencias de la Tierra, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, México.

[3] Instituto de Investigaciones en Ciencias de la Tierra, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, México – Centro Mexicano de Innovación en Energía Geotérmica.

omespinozaoj@conacyt.mx

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ABSTRACT

The suitable estimation of the geothermal potential from Geothermal and Petroleum Systems depends on the reliable knowledge from several geological, geophysical and geochemical parameters. A very important geophysical parameter is the heat flow, which can be used to describe the subsurface temperature profiles from the interest study zones, or vice versa, this allows to establish the areas with high temperatures/heat flow in the subsurface.

In this context, a computer simulator was developed to determine the geothermal potential from Mexican geothermal and petroleum zones. With the main objective to compute the conductive steady state thermal model, through a 2D numerical model of the heat transfer equations, applying the TDMA method (Tri-Diagonal Matrix Algorithm) as numerical solver of the equations. Therefore, 10 geothermal drilled wellbores located in a 4 km^2 area inside the La Primavera caldera (LP), Jalisco, México; and 39 petroleum wellbores located in 177 000 km^2 area in the northern of Chihuahua, México, were analysed. According to the obtained results from LP, under conductive conditions and steady state, the temperatures estimated are between 450 and 500 °C for a 3 km depth. Whereas, for the sedimentary basin of northern Chihuahua, assuming the same conditions as LP, the temperatures estimated are 175 to 190 °C.

1. INTRODUCTION

1.1 Geothermal energy in Mexico

Currently in Mexico, the growing demand for energy and the negative environmental impact generated to satisfy the demand through the use of conventional sources, has generated the search and therefore the use of diverse alternative energy renewable sources, such as solar, wind, and of course, geothermal energy. Which has a positive direct impact on the environment in addition to satisfy the energy demand.

According to data from the Secretary of Energy (SENER, 2015), at the end of 2014, reported that the capacity for generating electricity through renewable sources represented the 25% of the total generation capacity. Which, geothermal had a 1% share. In the same way, it was reported that the gross generation of electricity through renewable sources was 18% of total generation. From this percentage, only 2% corresponds to geothermal energy. Although it is known that Mexico has great potential for high enthalpy geothermal developments, as the current geothermal fields under operation for the generation of electric power, these have not been exploited to their maximum capacity or potential (Gutiérrez-Negrín et al., 2015). In addition, it is also known that a large number of sites contain thermal manifestations, considered as low and medium enthalpy (Iglesias et al., 2015), which could be proposed for their exploitation as direct use of geothermal energy (e.g., García Gutiérrez & Martínez Estrella, 2012). Even so, it has not been possible to explore and study them in detail, exist a considerable number of zones throughout the national territory with possible energy potential to generate electricity.

On the other hand, when the oil resources have been exhausted to an economically unviable point, the wellbores are abandoned or simply cease to be used. In some countries, such as Albania, China, Croatia, the United States of America, Hungary, Israel, New Zealand, Poland and Russia have supported economically research and work on the reuse of abandoned oil wellbores as source of geothermal energy (e.g., Davis & Michaelides, 2009; Noorollahi et al., 2015). To propose an abandoned oil wellbore for a geothermal project can reduce the investment costs of the project to more than 50%, which makes this option considerably attractive when it comes to a very large network of wellbores without being used, including complete oil fields. Conventional oil wellbores commonly have depths greater than 2 km and up to 7-8 km, that is, they are deeper than geothermal wellbores, which usually range between 2 and 3 km in depth. With these depths reached in the oil fields, it makes them a natural source of geothermal potential. For example, considering the natural geothermal gradient of the Earth, approximately 30 °C/km, at 5 km of depth, it could obtain temperatures of 150 °C. In Mexico, it is known that the vast majority of oil wellbores were drilled in areas that contain higher than normal geothermal gradients (e.g., Reiter & Tovar, 1982, Blackwell & Richards, 2004, Espinoza-Ojeda et al., 2017). Which makes them a potentially renewable, untapped source of geothermal energy.

According to the national inventory of thermal manifestations (Iglesias et al., 2015), the research works of Iglesias et al (2016), Espinoza-Ojeda et al (2017), and the National Inventory of Renewable Energies (http://inere.energia.gob.mx), there are many areas with possible geothermal potential, which have not been studied in detail, and because of this, the particular characteristics that define them as geothermal reservoirs are unknown. Therefore, in order to obtain a better and reliable geothermal potential model, geophysical thermal studies must be applied to estimate the thermal model from geothermal and petroleum zones.

2. STUDY AREAS

Nowadays, some institutions have again focused their attention on the development of geothermal energy in Mexico, proposing different research projects through agreements between the Secretary of Energy (SENER), the Federal Electricity Commission (CFE) and the Mexican Center for Innovation in Geothermal Energy (CeMIE-Geo). One of the interesting geothermal areas is La Primavera, which is currently studied by several academic institutions, including our research group. Another proposed study area for this work is the sedimentary basin from northern Mexico.

2.1 La Primavera, Guadalajara, Jalisco

The Volcanic Complex of La Primavera (LP) is located to the west of Guadalajara, Jalisco. With geographic coordinates 103º 28' to 103º 42' of longitude west and 20º 32'a 20º 44'of north latitude (Figure 1).

Located at the intersection of two Cenozoic volcanic provinces of Mexico, the Trans-Mexican Volcanic Belt (TMVB) and the Sierra Madre Occidental (SMO). Adjacent to an area of tectonic depressions of the Tepic-Zacoalco, Colima and Chapala rifts. Classified by Mahood (1981) as an extinct volcanic caldera followed by a series of magmatic episodes of rhyolitic domes. Currently, there is a recent geological map presented by Tinoco-Murillo (2017) from the area of La Primavera, Jalisco. Which the distribution of the Tuff Tala and the domes of the caldera is updated. In Figure 1 the relief and the location of the geothermal wells of La Primavera are shown.

2.2 Sedimentary basin from Northern Chihuahua

The region of the sedimentary basin of Chihuahua covers an area of approximate 177,000 km^2, which the inoperative oil wellbores are distributed. It is located in northern Chihuahua, Mexico, in the limit of the border with the United States of America. To the Southeast, adjacent to the Geological Province of Sabinas, to the South with the Coahuila Platform and to the West with the Sierra Madre Occidental (see Figure 2).

The Geological Province of Chihuahua is characterized by the presence of folded mountains affected by inverse faults and overcurrent that involve Mesozoic marine sequences. The mountain systems are separated by plains that arose when the depressions were filled by tectonic sedimentation (Barboza-Gudiño et al., 2016), with continental sediments and some lava flows (PEMEX, personal communication, 2013).

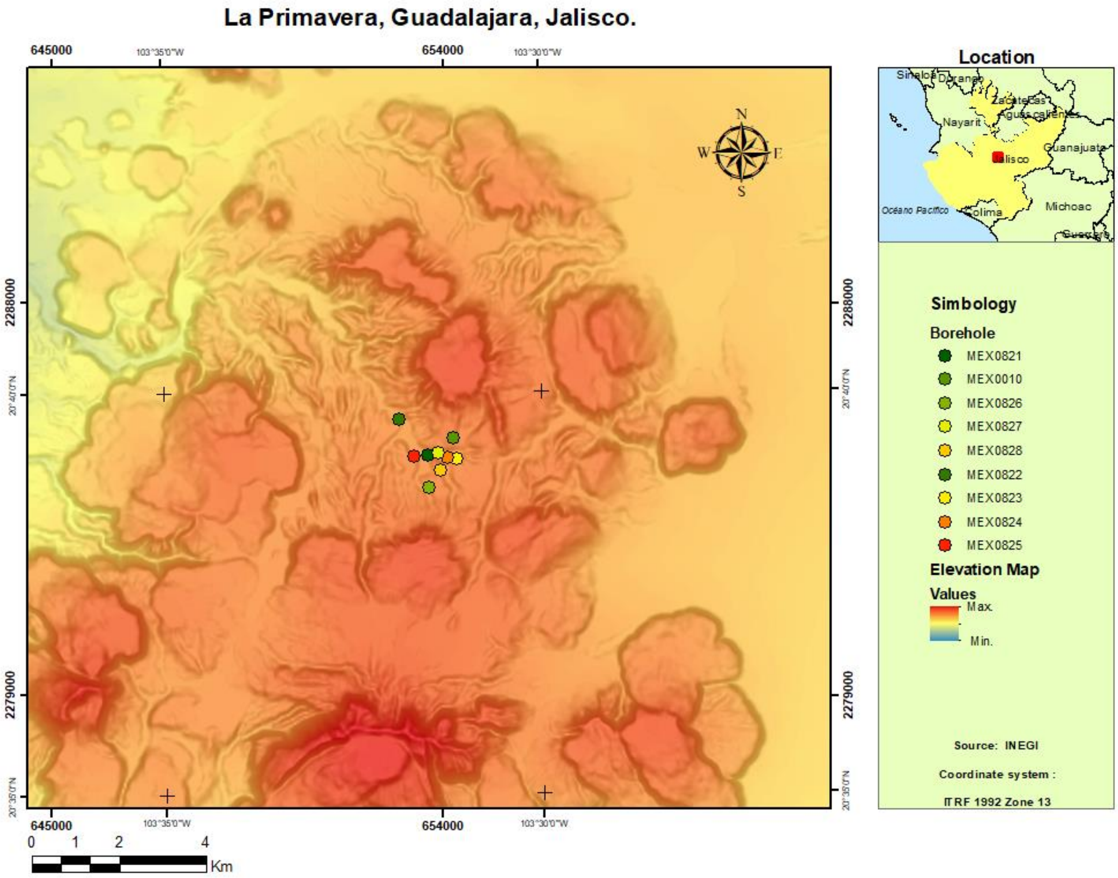

Figure 1: Elevation map of the geothermal zone of La Caldera of La Primavera, Guadalajara, Jalisco. Including the relief of the geothermal field and the location of the drilled wellbores.

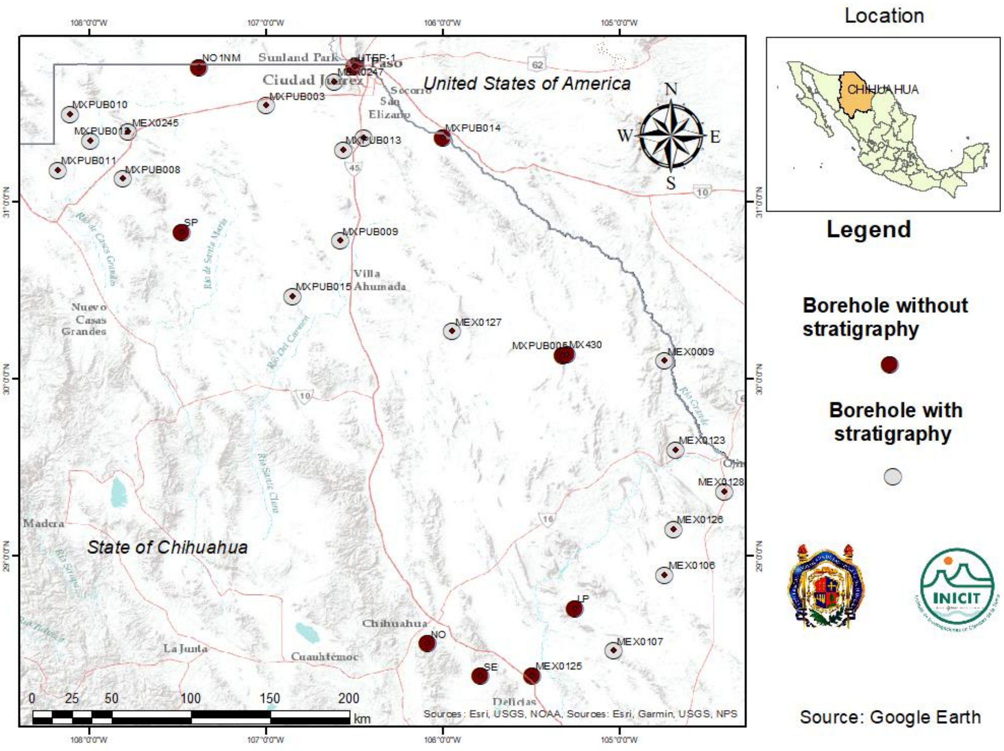

Figure 2: Location of the sedimentary basin from Chihuahua and distribution of the abandoned petroleum wellbores considered in this work.

3. METHODS

The methodology proposed in this research work consisted of a set of tasks that are described below:

3.1 Database

In order to create a database, first, it was carried out an exhaustive and detailed review of research works and technical reports related to the proposed study areas. With the purpose of a better detailed knowledge, as well as what kind of studies have been carried out in the geothermal and petroleum areas.

In the case of the geothermal wellbores of La Primavera, a review of technical reports provided by CFE was carried out (personal communication, 2017). While the Sedimentary Basin from Northern Chihuahua, the information was revised and compiled from the technical reports of abandoned oil wellbores (PEMEX, personal communication, 2013), and the complementation with published works related to these areas (i.e., Smith, 1974; Smith et al., 1979; Reiter & Tovar, 1982). Therefore, the compiled information consists of wellbore geology data, stabilized temperature logs, location data and supplementary data (i.e. thermophysical properties of rock formation, wellbore total depth, elevation, etc.).

3.2 2D Thermal model

In the development of the numerical simulation code, the equations were computed using Fortran as a programming language, which a conductive regime in a steady state was considered. It was idealized a scenario which the conduction dominates in solid rock without intervention of any type of fluid flow.

Starting from the Law of Heat Conduction or Fourier's Law, the differential equations of the model can be expressed from its general form:

$$q = -k\nabla T$$

Where q is the conductive heat flow, k the thermal conductivity and ∇T the Laplace operator to temperature. The characteristics of the reservoir model include variable thermal conductivities of the formation. The stabilized temperature records from each wellbore were used to validate the 2D model temperature calculations. Once the particular characteristics and conditions of the model are stablished, the domain/geometry of the model was designed.

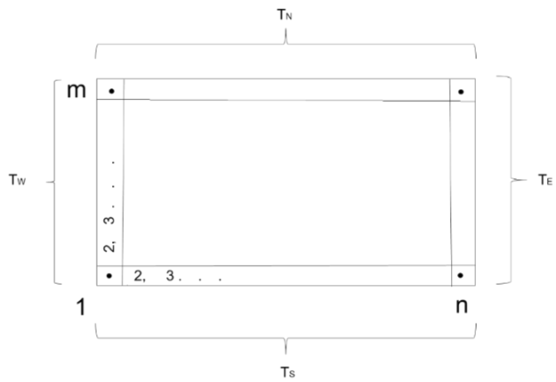

Figure 3: Geometric configuration of the 2D model for computational calculation.

Hence, it was defined a two dimensions (2D) geometric configuration of the model, developing a rectangular mesh to cover the calculation surface, where the lateral boundaries are defined by the wellbores and the upper limit is in contact with the topography. In this work the topography of the surface is negligible, which simplify the developing of a rectangular geometry. The successive changes of the rock layers depend on the depth. In the thermal modelling, the thermal conductivity values are assigned to each rock bundle and the thickness of the stratum is assigned.

The limits of the model are named as Northern Boundary (T_N), Southern Boundary (T_S), Eastern Boundary (T_E) and Western Boundary (T_W), as illustrated in Figure 3. The specific boundary conditions were assigned by means of numerical subroutines included in the 2D model, to calculate the temperatures.

The Numerical Method of Control Volume was used in the computer code to solve the differential equations and, in this manner, to obtain the temperature values from each point of the medium. This numerical method is based on the replacement of differential equations, by a set of algebraic equations that represent the unknown temperatures at the selected points in the model space. After the discretization of each control volume, a system of algebraic equations is obtained. These are distributed in a matrix that can be easily solved by the algorithm of Tridiagonal Matrix Algorithm (TDMA), which is based on Gaussian elimination (Patankar, 1980).

4. PRELIMINARY RESULTS

The application of the numerical tool developed to estimate the possible geothermal potential in petroleum zones and to better know the natural thermal regime in geothermal areas, led to interesting preliminary results.

4.1 Conductive steady state thermal model

To achieve this objective, it was necessary to develop a model that include real parameters of the system geometry (reservoir) and the consideration of anisotropic thermophysical properties, which depend on the stratigraphic configuration. In some cases, it is difficult to consider these adjustments in commercial or predetermined software. Hence, numerical programming is necessary, to develop models that integrate these conditions and adjust to the user needs.

The 2D thermal model was applied to La Primavera geothermal area, and the Sedimentary Basin of northern Chihuahua. In order to know their temperature field in steady-state conductive regime, according to their stratigraphy, it means, thermal anisotropic conductivities in function of the depth. This included consideration into the model makes more realistic the heat flow numerical calculations.

4.1.1 La Primavera

The volcanic field of La Primavera, is classified as a Caldera structure with acidic volcanic products (Mahood, 1981), where a remnant of the volcano-tectonic Quaternary activity, a deep convective hydrothermal system has remained (Maciel-Flores & Rosas-Elguera, 1992). In 1985, the CFE initiated a geothermal exploration project, which thirteen deep wellbores were drilled in the central part of LP. In this work nine wellbores were analysed in detail. With this information, the steady-state conductive reservoir temperature field was evaluated.

The most important assumption for the 2D model application in the LP, was to define an adequate depth of calculation. The works of Verma & Rodríguez-González (1997), Verma et al. (2012) and Verma & Gómez-Arias (2016), evaluate the behaviour of the heat flow of the magmatic chamber, using numerical modelling. The average depth for their models which the effects of the heat source are reported, is above five to ten kilometres. In order to avoid interference from the convection mechanism that governs in the vicinity of the magmatic chamber. The maximum depth defined for the computational calculation of this work was three kilometres and the length depend on the distance between the wellbores. The temperature calculation to the maximum depth is done by extrapolation, using the average conductive heat flow.

The Northern boundary condition is equivalent to the surface temperature, in this case, from 28 to 32 °C (INEGI, 2017).

The Eastern and Western Boundaries condition depend on the stabilized temperatures of the wellbores involved in the calculation. As an example, in Figure 4, the thermal profiles from MEX0821 and MEX0825 wellbores are plotted. These temperature-depth data were used for the calculation of the thermal sections. In Figure 4, can be observed that the conductive zone of the formation predominates on average up to 1000 meters depth, since the temperature increase generally has a linear tendency. After the 1000 meters of depth, the conductive-convective zone begins, fractured or permeable rock could be the main cause. This means that the heat conduction is disturbed by the fluid flow, which causes a drastic temperature decrease, breaking with the linear trend of temperature-depth increase. The heat transfer theory establishes that the heat flows from the deepest to the surface, therefore, in a purely conductive process, the temperature-depth increase (or geothermal gradient) has a linear trend. The efficiency to transport the heat through the rock formation can be measured with the thermal conductivity of the rock. This parameter affects directly to the geothermal gradient. Therefore, the linear trend cannot be constant due to the non-homogeneous rock composition of the subsurface, producing changes in the geothermal gradient according to the stratigraphic variation (rock formation), but remaining the linear trend (e.g., Bullard, 1939; Lee, 1965, Blackwell, 1971, Chapman & Rybach, 1985, Haenel et al., 1988, Čermák & Rybach, 1991, Beardsmore & Cull, 2001).

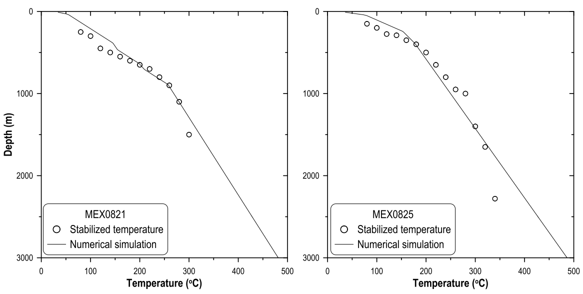

Figure 4: Thermal profile plots of MEX0821 and MEX0825 geothermal wellbores from La Primavera. Including actual stabilized formation temperature and numerical calculation of temperature.

Therefore, ¿What would happen if the LP reservoir was supposed to be completely conductive? ¿What would be the natural thermal state of LP without convective disturbance? These questions can be very delicate from the point of view of the reliable and realistic evaluation of geothermal resources, but they are valid if the appropriate treatment of existing data is done. The numerical calculation of temperature from the assumption of purely conductive heat transfer answered these questions (see Figure 4). The variation of the thermal conductivities is expressed in the model, according to the geological composition of the wellbores.

For practical purposes in this work it was decided to divide the sections according to their orientation. As example, in Figure 5, a West-East profile is shown (MEX0825-MEX0821). And a North-South profile (MEX0821-MEX0826) is described in Figure 6.

4.1.2 Sedimentary basin from Northern Chihuahua

Northern Chihuahua is located in a large Sedimentary Basin (Barboza-Gudiño et al., 2016), where currently abandoned petroleum wellbores were drilled by PEMEX. Reiter & Tovar (1982) reported geothermal anomalies, according to some medium and high heat flow values estimated from some wellbores located in this region.

The few studies about the geothermal potential of the sedimentary basins in Mexico were the main motivation of this work. The objective is to obtain an overview of the heat flow distribution in the abandoned petroleum wellbores.

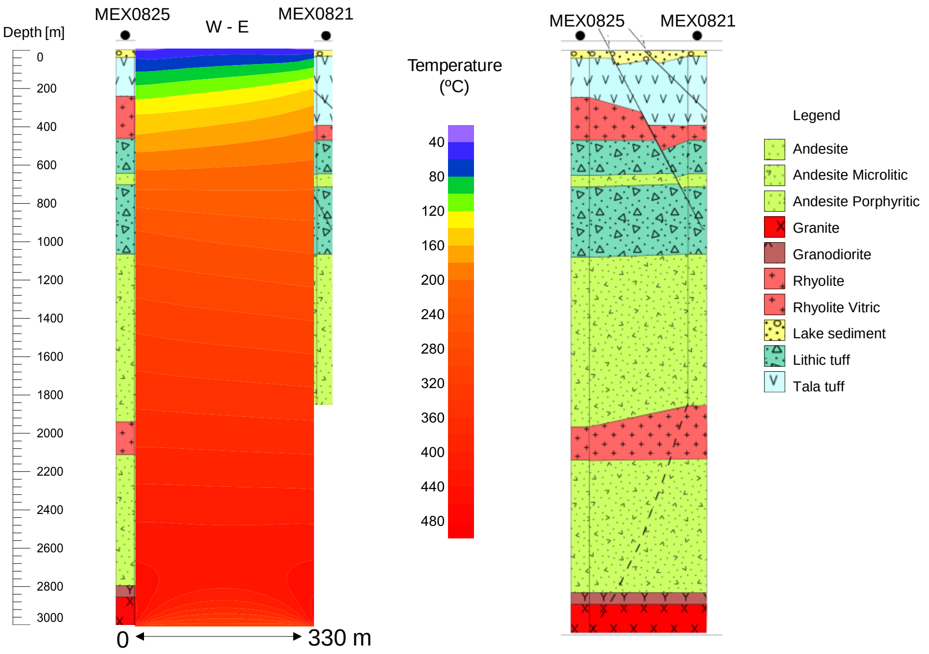

Figure 5: 2D thermal profile from MEX0821 and MEX0825 geothermal wellbores from La Primavera. Including stratigraphic model.

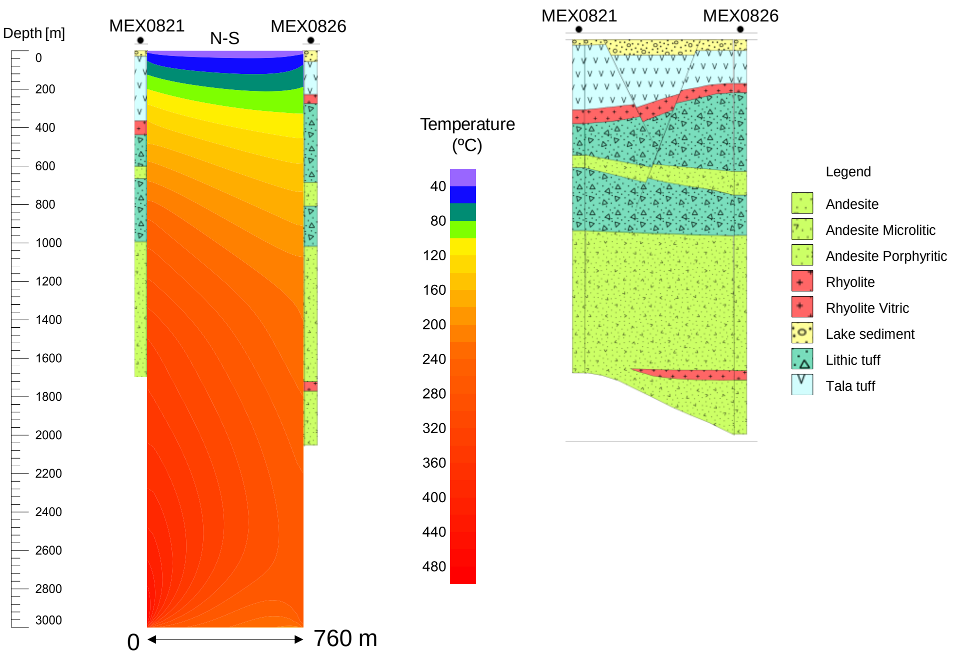

Figure 6: 2D thermal profile from MEX0821 and MEX0826 geothermal wellbores from La Primavera. Including stratigraphic model.

The anomalies in the sedimentary basins are often attributed to the influence caused by the structural system of extensive type, characterized by normal faults systems and the crustal thinning by the tectonic formation of rifts (Moeck, 2014). The zones of cortical weakness favour the ascent of plutonic bodies that generate thermal manifestations.

Moeck (2014) stated that conductive heat transfer predominates in sedimentary basins geothermal systems, although there are exceptions in areas with fluid interference. In the case of abandoned petroleum wellbores, considered in the thermal numerical simulation of this work, no fluids have been reported in the system (Reiter & Tovar, 1982; Espinoza-Ojeda et al., 2017). The 2D model calculates the conductive thermal steady-state, which is the first approximation of the temperature distribution of this kind of system in Mexico.

The area of the abandoned petroleum wellbores covers approximately 44,000 km^2. As illustrative example, in the Figure 7, the thermal profiles from the correlation between the petroleum wellbores MXPUB009-MXPUB015-MEX0127 are shown.

5. GENERAL DISCUSSIONS

In the thermal section MEX0825-MEX0821 (see Fig. 5), the isotherms behavior depends on the stratigraphic distribution of the wellbores, due to the thermal conductivity values. The first 400 meters are made up of layers formed by lake sediments and pyroclastic flows, corresponding to the Tuff Tala formation, the small consolidation of materials and their high porosity attribute low conductivities (<1.5 W/mK), working as insulating materials, which causes temperatures lower than <100 °C. The following layers are rhyolite, lithic tuff and andesite, which support temperature increase from 100 to 300 °C.

In the correlation between MEX0821-MEX0826 (see Fig. 6), the range of the temperatures calculated at 3000 meters depth are from 440 to 480 °C. It can be noted that the sections in this orientation cut the geomorphology where there are small grabens limited by normal faults to the end point, which are associated with the sinking of the volcanic event that formed the LP Caldera (Mahood, 1981). In the stratigraphic correlation (Fig. 6), two normal faults that form a small graben are located. These displacements were considered in the construction of the 2D Model.

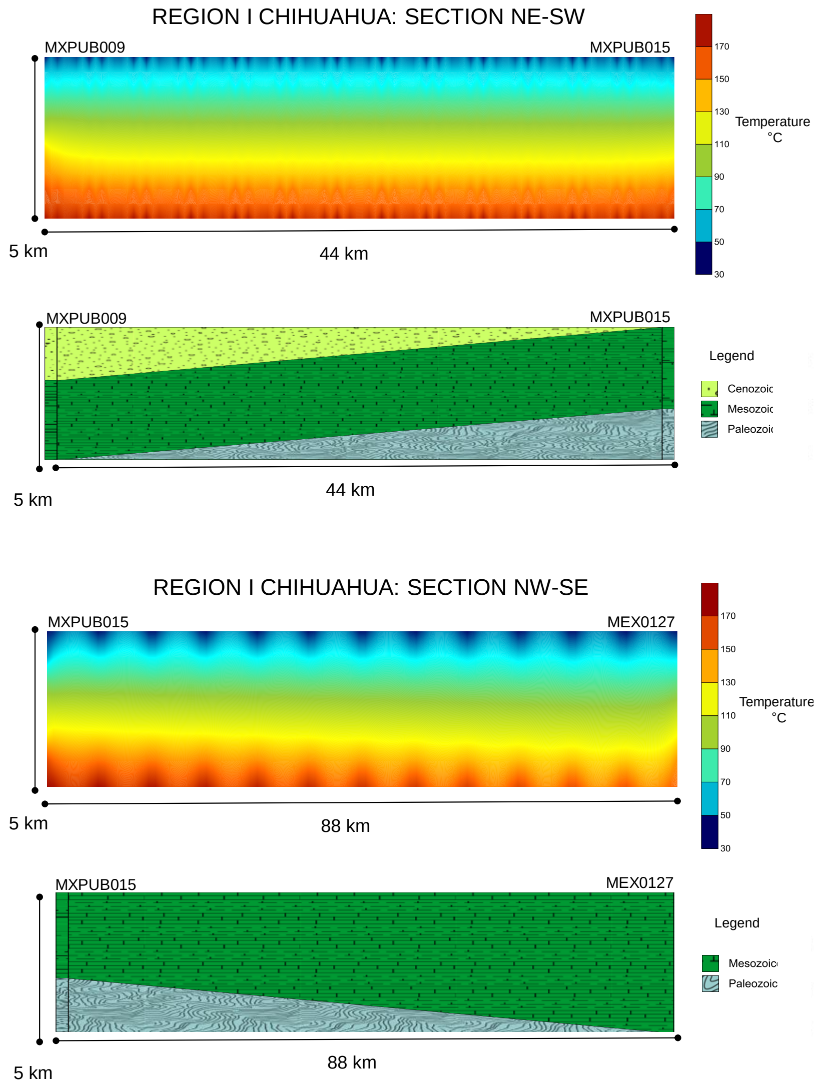

Figure 7: 2D thermal profiles from the petroleum wellbores MXPUB009-MXPUB015-MEX0127 located in the sedimentary basin. Including stratigraphic model.

In summary, from the thermal profiles shown in Figs. 5 and 6, it was possible to represent the natural thermal conductive steady-state from La Primavera, according to the analysis and assumptions proposed in this work. The high temperatures estimated in the reservoir at 3000 m depth, indicate that LP is with certainty a high temperature geothermal system. Emphasise that these estimated temperatures are the product of assuming there is no convective zone in the subsurface, as shown in the temperature-depth profiles (Fig. 4). The conductive pattern observed in the thermal profiles, when is extrapolated, gave the results reported. In other words, the estimated temperatures at 3000 m depth are the theoretical temperatures that reproduce the temperatures logged in the conductive zone of the reservoir. In addition, from Fig. 4, it can be observed that the temperatures of the conductive-convective zone are around 300 °C (1000-1500 m depth). Hence, to support the obtained results in this work, these are agree with the results of numerical simulation by Verma et al. (2012) and Verma & Gómez-Arias (2016), which the magma chamber temperature was evaluated.

On the other hand, the reported stratigraphic data from the abandoned oil wellbores were used, in order to have a more realistic behavior of the thermal model. In the facies changes of the sedimentary rock packets that have a similar conductivity, their average value was applied, with the purpose to simplify the compute calculations. Sedimentary rocks have thermal conductivity values of approximate >1.5 ~ 2.5 (W/mK), according to reported values by Sundberg et al. (2009), Wen et al. (2015) and Merriman et al. (2017).

The section MXPUB009-MXPUB015 (see Fig. 7), shows a temperature distribution from 160 to 170 °C, where the isotherms behave uniformly, which indicates that the heat flow is similar to both oil wellbores. Their stratigraphy, sedimentary and metamorphic rocks belonging to the Paleozoic are located, followed by an alternation of carbonate rocks with Mesozoic clastic rocks. Finally, the summit is formed by sediments of the Cenozoic. As the consolidation of the rocks increases, the heat flows proportionally in this profile.

In the case of the MXPUB015-MEX0127 profile, the isotherms increase towards the wellbore MXPUB015, where the maximum temperature calculated is 175 °C at 5 km depth. While the MEX0127 isotherms oscillates in values from 150 to 170 °C, as it is illustrated in Fig. 7. The characteristics of the wellbore MXPUB015, whose depth is 5000 m and its elevation 1296 masl. Its stratigraphy is made up of Paleozoic rocks, to the top a pack of clastic rocks and sediments of the Mesozoic. The average thermal conductivity of these rocks is 2.93 W/mK and the reported heat flow is 85 mW/m^2. The wellbore MEX0127, with depth up to 7050 m and 1400 masl. Its average heat flow is 77.9 mW/m^2 and the stratigraphy constituted by Mesozoic rocks have an average thermal conductivity of 2.38 W/mK.

The numerical analysis of the sedimentary basin of Chihuahua, established the first approach of the subsurface thermal profiles. However, the main disadvantage has been the large distance between the wellbores (> 10 km), and the small successive changes of the formation layers, difficult to represent in detail at large scales. To solve this problem, a chronostratigraphic correlation by geological ages were used. The maximum estimated temperatures were 190 to 210 °C. Proposing this type of geothermal resource as medium to high enthalpy.

6. CONCLUSION

The maximum temperatures calculated at 3 km depth, for the N-S profiles were 450 to 510 °C, and for the W-E orientation were 400 to 480 °C. Therefore, the preliminary results for La Primavera describe it as high enthalpy geothermal reservoir. Besides, the numerical results are agreed with Verma et al. (1997, 2012).

More detailed geological and geophysical data are required to develop an accurate and reliable geothermal conceptual model from La Primavera.

The sedimentary basin, according to the numerical results and the analysed area, could be consider mainly as a low-medium enthalpy geothermal system. Direct uses could be applied to exploit the heat reserves. In addition, it is possible to identify the sites with possible subsurface thermal anomalies.

Thermal conduction is assumed to be the main heat transport mechanism that dominates the sedimentary basin reservoir. However, due to the dimension scale considered in this work, the presence of convection or anomalies in the area could be possible.

As future work, the proposed 2D numerical model must be developed into 3D, considering a conductive-convective heat transport mechanism.

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