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Thermal Assessment of Los Humeros Geothermal System Through Basin Modeling

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ABSTRACT

The Serdán-Oriental Basin is located at the eastern margin of the TransMexican Volcanique Belt, central Mexico. The main feature of the Serdán-Oriental Basin is the Los Humeros Volcanic Complex (LHVC), a complex caldera system continuously active for the past 3 Myr. The main volcanic event of the LHVC is formed by the two caldera forming Xaltipan and Zaragoza ignimbrites, that occurred respectively 164 and 69 kyr ago. The LHVC has thus been separated in 3 phases (pre-caldera, caldera, and post-caldera). All this volcanic activity, as well as the plinian activity between the ignimbrites and the numerous monogenic volcanism, is to be related to magmatic storage that creates a significant heat source bellow the LHVC. This heat source, combined with an active hydrological system, has created a dynamic geothermal system that is in exploitation in the central part of the Los Humeros Caldera with an installed capacity for electricity generation of 93 MW produced from 20 wells.

With the aim to better understand the geothermal system, we used a basin modeling tool, TemisFlow®, to build a 2D model across the Serdán-Oriental Basin. The modeling of the Serdán-Oriental Basin's thermal structure concentrates on two aspects, the heat source generated by the storage of the magma in the crust, and the hydrological system that increase the temperature in certain areas at shallower depth through the advective transport of the heat. The geometry considered is a thick limestone layer covering the crystalline basement and overlaid by the LHVC. The LHVC magmatic system has been considered with the emplacement at shallow level (5-7 km depth) of large magmatic chambers during the caldera phases, creating a composite heat source. In addition to these shallow systems, deeper storage have been considered, creating a high background temperature. Results of the simulations show still a significant impact of the remnant heat from the ignimbrite related magmatic chambers and a variability increased by the hydrological driven advection. Through this work, we can clearly see the interest of using powerful O&G modeling tool such as TemisFlow® and adjusted for geothermal energy, helping the exploration of green field or guiding further development in existing geothermal energy systems.

1. INTRODUCTION

Basin modeling is an integrative tool traditionally used to assess petroleum systems evolution through time (Ungerer *et al.*, 1990; Schneider *et al.*, 2000; Al Hajeri *et al.*, 2009; Hanstchel and Kauerauf, 2009). By simulating the thermo-chemical-mechanical processes throughout the basin geological history, it allows not only to better apprehend the hydrocarbon generation and migration processes, but also to assess the main parameters that guide these processes. As a consequence, the porosity and permeability of the different facies, as well as pressure, temperature and several others parameters are calculated and can also be used for the evaluation of geothermal systems.

In the case of the Serdán-Oriental Basin, in which the thermal structure of the LHCV is still affected by recent (<1My) magmatism, basin modeling can be effectively used to evaluate the thermal effect of these intrusions. The temperature profile along the section through time is calculated using a conservative heat equation that accounts for both conductive and advective heat transfers (equation 1; modified from Agelas *et al.*, 2001 and Lemgruber-Traby *et al.*, 2020). It takes into account a top and bottom thermal boundary condition, the initial temperature of the intrusive bodies and its cooling with time. Thermal properties are estimated for the porous media, according to lithological and fluid properties behavior defined for each facies,

$$\frac{\partial}{\partial t}(\rho c_b T) + \mathrm{div}\left(\left(\rho_w \Phi c_w T\overrightarrow{V_w}\right) + \rho_s(1-\Phi)c_s T\overrightarrow{V_s} - \lambda_b \overrightarrow{\mathrm{Grad}}T\right) = q_h + q_r + q_i \qquad \textbf{Equation 1}$$

Where: ρc_b is the heat capacity of the saturated porous media and λ_b its thermal conductivity, which depends on the porosity, saturation and the thermal conductivity of the phase; Φ is the porosity; ρ_w and c_w the density and heat capacity of water, respectively; V_w is the velocity of water, obtained from Darcy law generalized in function of pressure. The right side members of the equation correspond to heat sources associated to radiogenic heat generation (qr), heat linked to the sediment deposition or erosion, considering that the sediments are deposited with the same temperature as the top of the basin and that the eroded sediments take with them an amount of heat proportional to its temperature (q_h); and the heat linked to the magmatic intrusion considering a defined liquefaction temperature (q_i)

The precision of the results depends directly on that of the defined model, but even when relatively few data is available, basin modeling can be used to test scenarios, evaluate hypotheses and reduce exploratory risk. For the purpose of this study, we used only public available data (Jolie *et al.*, 2018; Carrasco-Nunez *et al.*, 2018; Lucci et al., 2020) and performed different scenarios aiming to investigate the role of fluid circulation and magmatic intrusions in the thermal structure of LHCV.

2. GEOLOGICAL SETTING

The Los Humeros Volcanic Complex (LHVC) is a large caldera system that developed at the eastern margin of the TransMexican Volcanic Belt since the Pleistocene (figure 1). The system is nested within the Serdán-Oriental Basin that defines the underlying basement to the volcanic sequence, and that tops up the crystalline Upper Crust defined as the Teziutlán Massif. The Serdán-Oriental Basin is composed of a thick Jurassic-Cretaceous limestone ensemble. Its sedimentary deposits are composed of highly folded and trusted shale and limestone deposited during the Jurassic and Cretaceous (Viniegra-Osorio, 1965). This ensemble can be observed on the edge of the basin, showing a mainly calcareous deposition with occasional shale interbeds. The LHVC developed over this crystalline and sedimentary basement during three phases, with a major caldera forming events at the center of it. The timing of the different phases, presented in figure 2, has been recently revisited by Carrasco-Nunez *et al.* (2018).

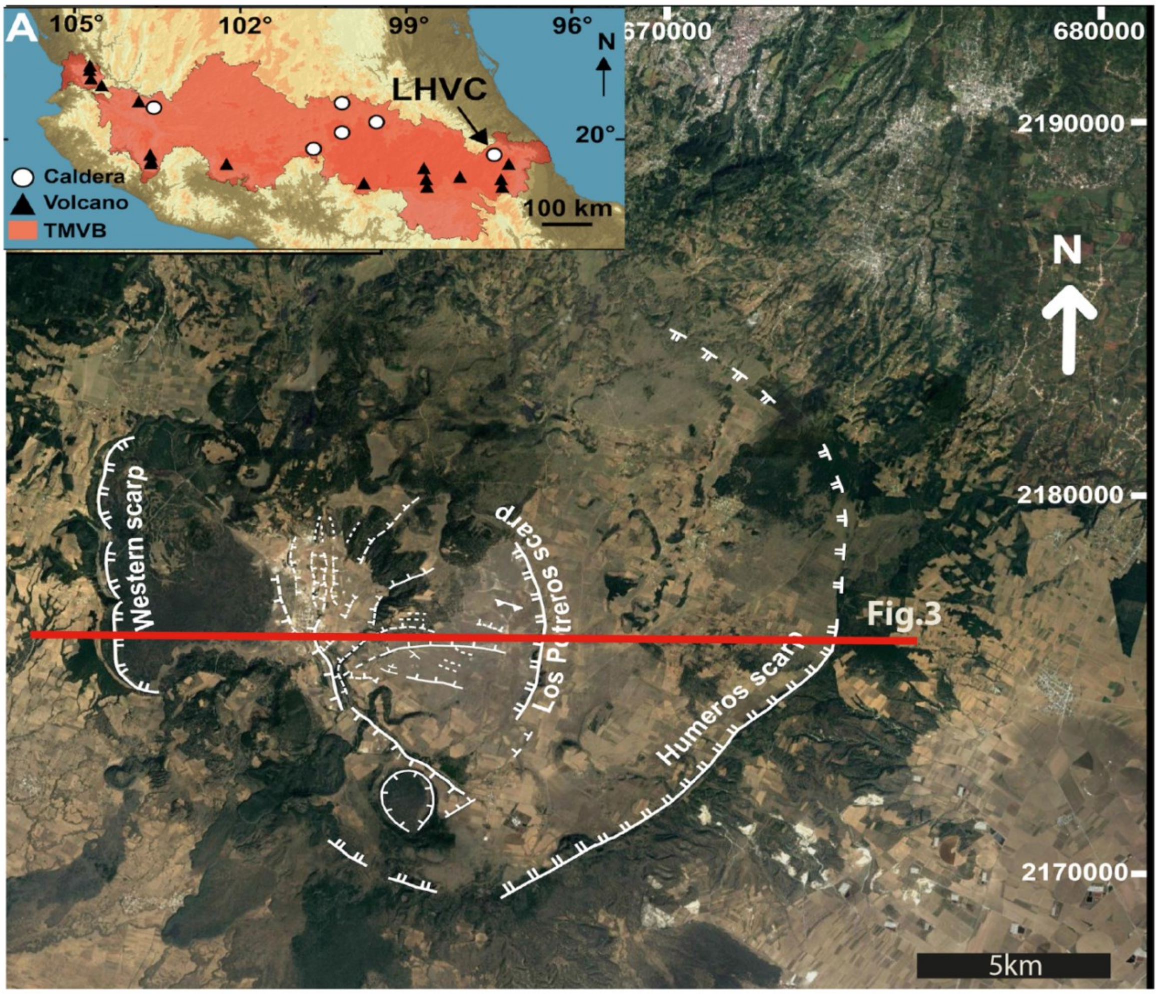

Figure 1: Location map of the nested bowl shaped Los Humeros Volcanic Caldera (modified from Carrasco-Nunez *et al.*, 2018). Red line indicates the location of the cross section modeled in this study and presented in figure 3.

Anterior to the volcanic activity associated with the LHVC, andesitic to basaltic volcanic deposits from surrounding volcanic centres are being recorded (e.g. Cerro Grande volcanic complex, Cofre de Perote, Cerro Pizarro-Águilas). The pre-Caldera stage of Los Humeros then developed between 700 and 270 ka with predominant Rhyolite domes. The main forming event in the LHVC is the creation of the calderas in two stages that is recorded through two ignimbrites (figure 2). The first sub-stage is the creation of the main Los Humeros Caldera at 164 ka with the Xaltipan Ignimbrite (Ferriz and Mahood, 1984) estimated at 115 km^3 DRE. This is followed by a Plinian phase as an "interlude" before the second nested caldera forming of Los Potreros at 69 ka associated with the Zaragoza Ignimbrite of "only" 15 km^3 DRE (Carrasco-Núñez and Branney, 2005). Finally, the post caldera-stage is defined by a mostly monogenic extrusive magmatism with a very diverse composition from the undifferentiated olivine-bearing basalts to Rhyolite domes. The first identified sub-phase is a resurgent phase, creating an inversion of some of the faults created during the caldera phase, followed by a ring fracture activity.

The resulting LHVC present day structure (figure 3) is a nested bowl shaped caldera system lying on a thrusted and folded limestone from Jurassic-Cretaceous and of up to 3 km thick. These sediments are topped by a thick Teziutlán pre-LHVC andesitic lavas (of over 2 km at the centre). The thin monogenic magmatic that relates to the pre-caldera stage is followed by two caldera stage ignimbrites (about a kilometre in thickness) and a thin (few hundred meters) of high magmatic diversity that forms the post-caldera stage.

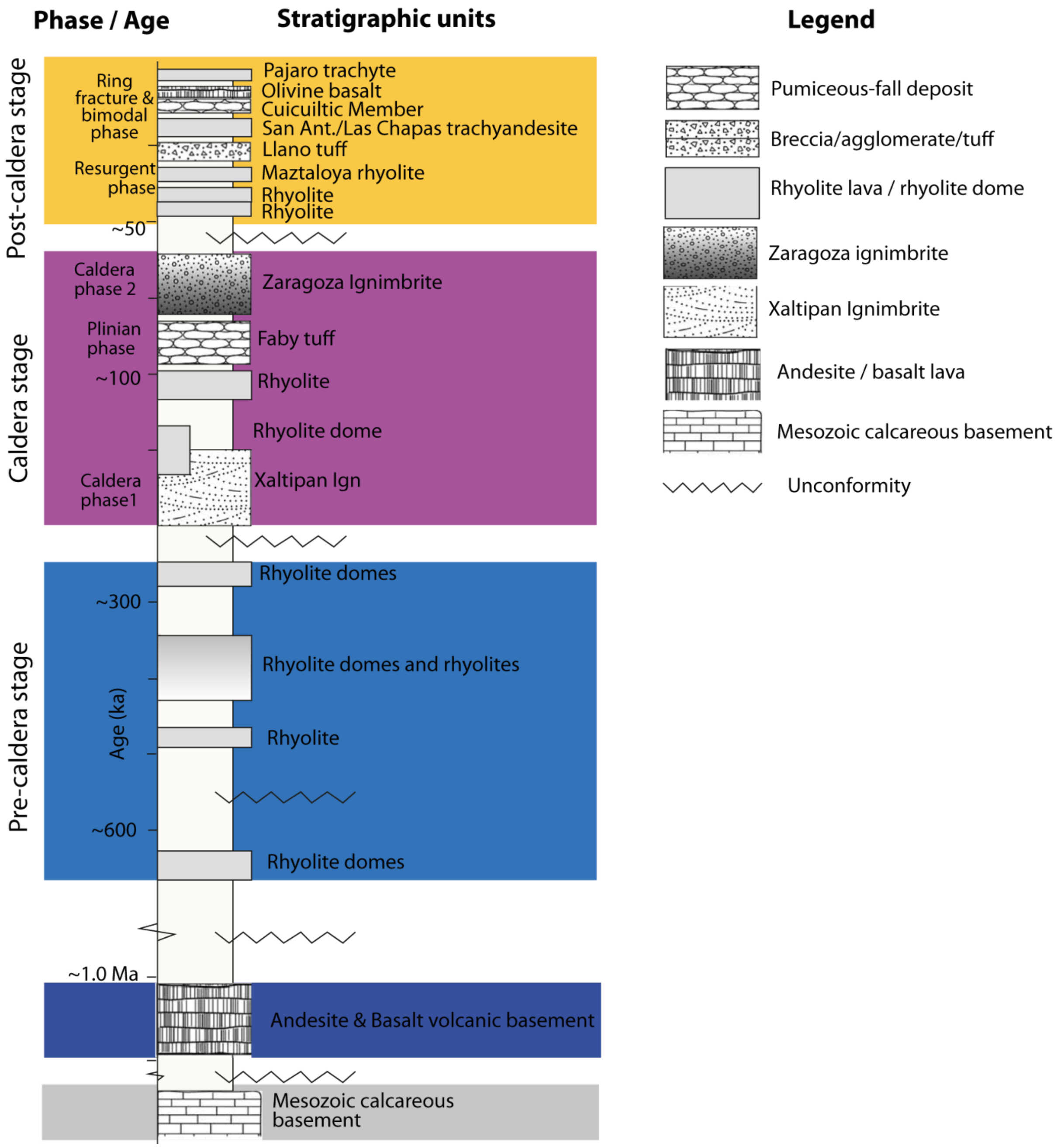

Figure 2: Stratigraphic framework for the volcanic units exposed at LHVC (modified from Carrasco-Nunez *et al.*, 2018 and Calcagno *et al.*, 2020)

2.1 Magmatic sequence

The GEMex projet (Jolie *et al*., 2018) and more specifically the work of Lucci *et al*. (2020), has led to a better understanding of the magmatic plumbing system. It has allowed to understand the complexity of the system below the LHVC mostly defined by short lived magmatic bodies creating a network of heat sources at different stages of cooling. The deeper part is characterized by large magmatic storage at a Lower-middle crust boundary (~30 km depth) described as anhydrous Ol-basalt at a temperature of 1250°C. The second storage depth is located at the Middle-Upper Crust boundary at ~15 km depth with a temperature assessed between 979 and 1263 °C that relates to the magmatic diversity in composition. Finally, the last magmatic storage, that can be described as the magmatic chamber of the calderas (and therefore source of the ignimbrites), is at a depth between 3 and 7 km depth for a temperature of around 1000°C. To these large storage, smaller storage have been identified at depth between 2 and 4 km and as to be the source for the monogenic magmatism seen at the surface. In addition to these main storages, a network of dykes and sills allow the temperature to remain high in the whole system. The importance of this information is to provide a thorough input of the heat that is provided to the system in addition to the average heat flow that has been assessed between 73 and 83 mW/m2 (Pollack *et al*., 1993).

3. LOS HUMEROS 2D BASIN MODEL

For the purpose of modelling, an homogenous temperature of 1000°C at approximately 8km below surface, i.e. at the base of the model, has been considered. This is then being perturbed by the successive arrival of two magmatic pulses that have created the caldera forming ignimbrites. First, at 164 kyr, a larger magmatic chamber associated to the Los Humeros caldera was defined within the continental crust below the Jurassic-Cretaceous limestone ensemble, along the entire modelled section. Later, at 69 kyr, a smaller magmatic chamber, was defined also within the continental crust below the Jurassic-Cretaceous limestone ensemble, but restricted between the Western Los Humeros and the Los Potreros ring faults (figure 3). The initial temperature of the magmatic material was defined as 1000°C.

The facies' porosity and permeability curves and their thermal properties (matrix thermal conductivity, heat capacity and radiogenic heat generation) were defined according the facies mixture, by using TemisFlow® lithological library and adjusting them according to available information from Deb *et al*. (2019) and Bonté *et al.* (2019) (table 1). Fluid circulation was simulated both through the porous media and through the main faults presented in figure 3.

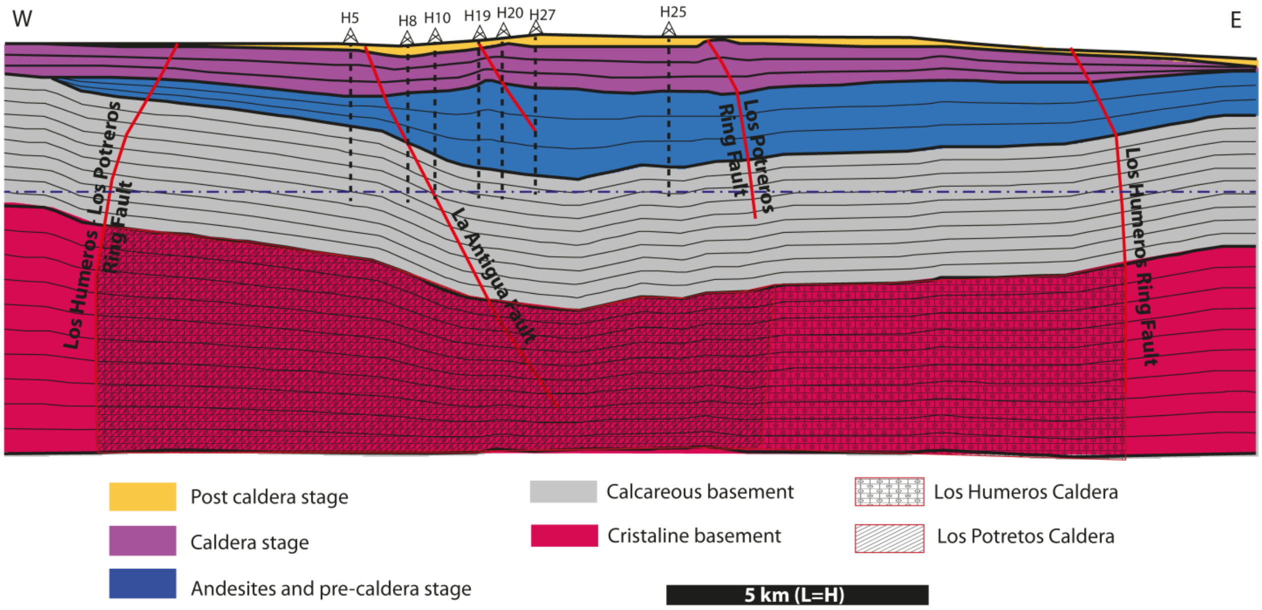

Figure 3: Modeled section modified from Carrasco-Nunez *et al.*, 2018 and Calcagno *et al.*, 2020. Location of the section is presented in figure 1. Red lines are the main faults of LHVC. The wells projected along the section were used for the thermal calibration. The dash-dotted blue line corresponds to sea level.

Units	Rock description	Solid density (kg/m3)	Surface matrix conductivity (W/(m*°C))	Mass heat Capacity (J/(kg*°C)	Radiogenic production (W/m3)
U1 Undefined pyroclastic	Tuffs, pumices, & some alluvium	2340	1,91	862	5,0E-07
U2 Post caldera	Rhyodacites, andesites, basaltic andesites, and olivine basalts lava flows, with ages between 0.05 and 0.03 Ma	2650	2,18	768	5,0E-07
U3 Los Potreros caldera	Rhyodacitic flows and Zaragoza Ignimbrites	2450	2,74	864	1,5E-06
U4 Intermediate	Faby Tuff & andesitic-dacitic lava flows (0.27 to 0.19 Ma) Rhyolitic and obsidian domes (0.36 to 0.22 Ma)	2450	2,31	813	1,5E-06
U5 Los Humeros caldera	Mainly the Xaltipan Ignimbrite with minor andesitic and rhyolitic lavas (Quaternary)	2450	2,74	864	1,5E-06
U6 Upper pre-caldera	Rhyolites, dacites, some andesites and tuffs and minor basalts	2700	2,31	738	1,8E-06
U7 Intermediate precaldera	Mainly pyroxene andesites (Teziultán Andesites) with mafic andesites in the basal part and/or dacites (Plio-Quaternary)	2710	2,14	790	1,1E-06
U8 Basal pre-caldera	Mainly hornblende andesites (Alseseca Andesites & Cerro Grande) and dacites - Miocene	2700	2,63	788	1,1E-06
U9 Basement	Middle Miocene granitic intrusions Cretaceous limestone and shales and minor flint Jurassic limestones and shales	2740	4,2	804	6,2E-07
U10 Basement	Paleozoic granites and schists (Teziultán Massif)	2900	3	941	2,5E-06
Water	Brackish water	1007	0,6	3975	-

Table 1. Main thermal parameters defined for the different units. The water parameters is also presented.

3.1 Thermal Results

The model results show that the thermal structure of the LHVC is still affected by the recent magmatic activity (figure 4), even at shallow depths. The present day temperatures obtained from the basin modeling of the LHVC were compared to the measured temperatures gathered for 7 wells along the modeled section (figure 3). The comparison of the obtained results with the available data shows good calibration for 6 of them (figure 5). We interpret these results as a good calibration of the LHVC overall temperatures, associated to the heating generated from the Los Humeros and Los Potreros caldera phases. Alternative scenarios were performed aiming to understand the misfit observed at well H8, for which the temperatures were respectively underestimated and overestimated by the model results.

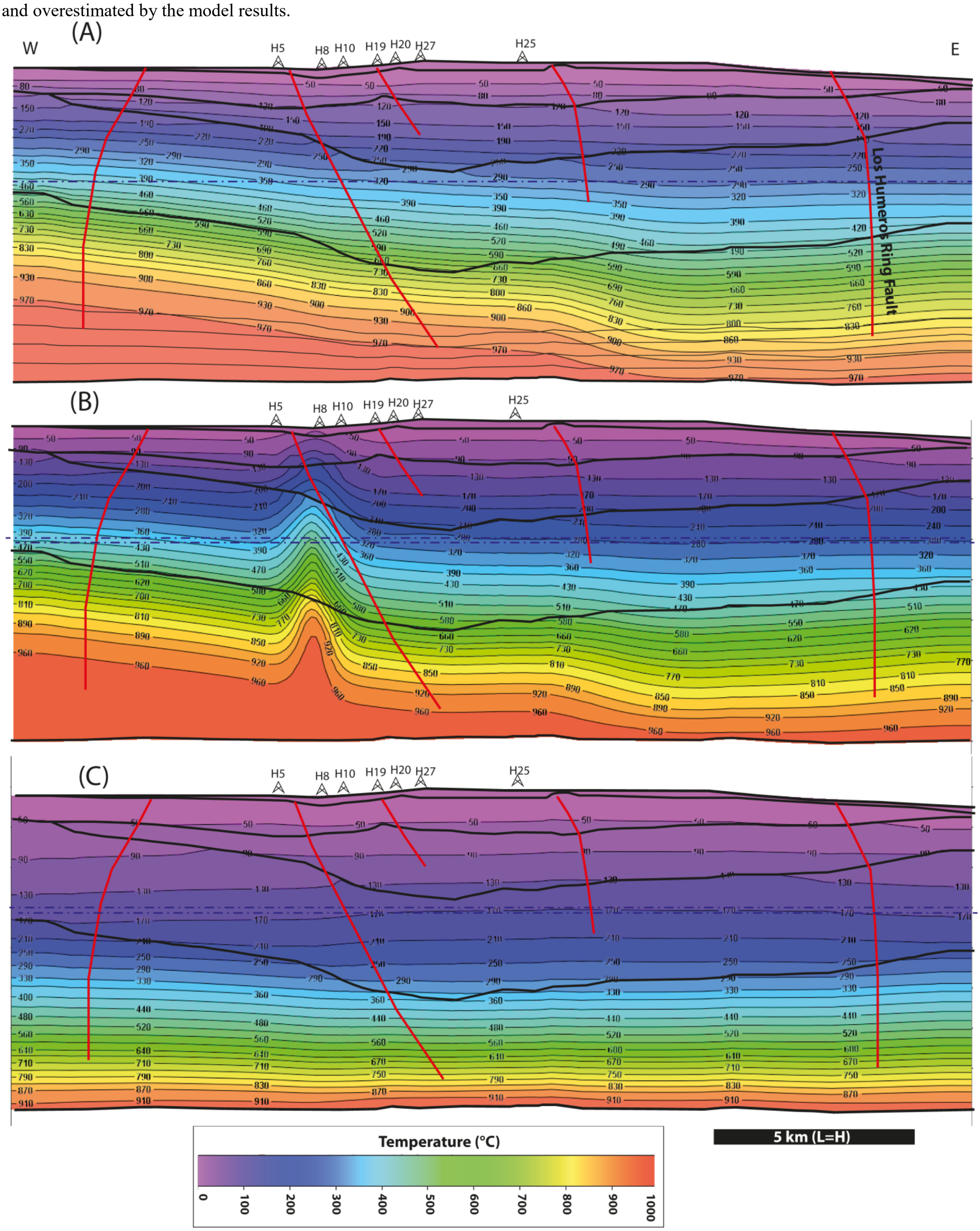

Figure 4: Temperature results obtained from basin models. Location of the section is presented in figure 1. (A) is the reference scenario considering the magmatic chambers associated to the Los Humeros and Los Potreros calderas; (B) takes into account a hypothetical recent intrusion, that allowed the calibration of well H8; (C) shows the thermal results obtained without taking into account any magmatic intrusions.

The model thermal calibration at well H8 was only satisfactory when considering a recent local magmatic intrusion (figure 4C and 5). But the proximity of this well with H10 well, that present a lower geothermal gradient, made it difficult to assure the calibration of the two wells. The precise prediction of local temperatures variations seems to require the identification of the location of recent dikes and sills.

A particular attention was also given to the fluid circulation from the surrounding mountains, that assures the water recharge and maintain the system active. Fluid circulation was considered both through the porous media (considering their calculated porosity and permeability) and through the defined faults. Nevertheless, the consideration of advective heat transfer by these fluids had only limited effect on the temperature results of the analyzed wells.

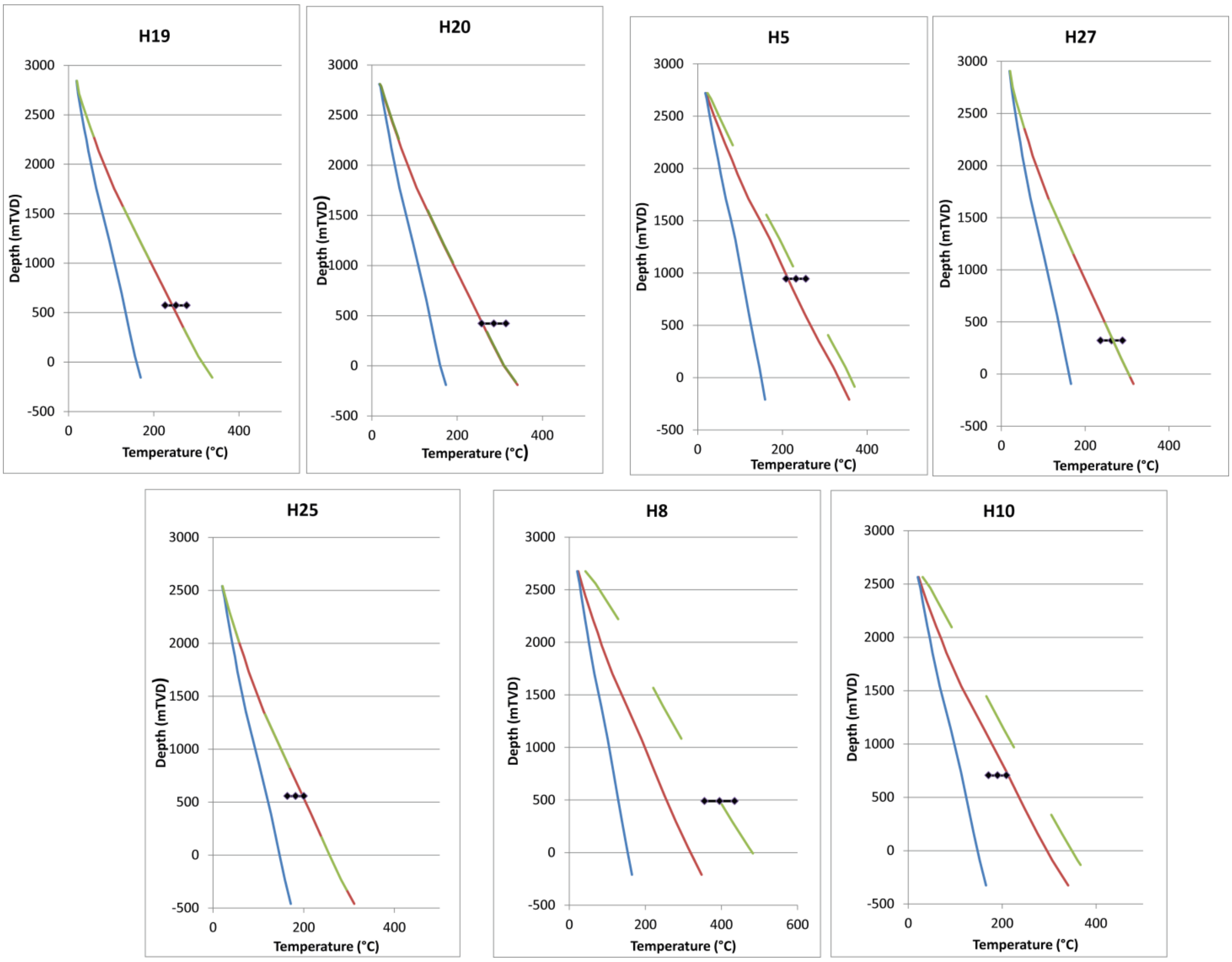

Figure 5: Comparison of temperature extracted from the model at the location of the 7 wells presented in figures 3 and 4, with the well temperatures gathered from Bonté *et al.*, 2019. Black dots and lines correspond to well temperatures with a 10% error bar. The red lines correspond to extraction from the reference model (A in figure 4), green dashed lines correspond to model considering a recent localized intrusion (B in figure 4), blue lines shows the results without taking into account any magmatic intrusion (C in figure 4).

4. DISCUSSIONS AND CONCLUSIONS

Using basin modeling tools, originally developed and used for oil and gas exploration, gives useful information for geothermal resources evaluation. This work made only use of standard functionalities, already available in the basin modeling software. The possibility of taking in consideration the past arrival of a hot material (magmatic bodies), its cooling through time, and its effect on the system thermal structure was key for this study. This functionality is usually used to evaluate its impact on the source rock maturity, but here we only analyzed its impact on present day temperatures.

One challenge for the use of basin modeling tools for geothermal resources evaluation is the difference of the scale of interest, both spatial and temporal, in relation to oil and gas studies. But this work showed that relatively small time events (tens of thousands years) can be taken into account. It also showed good results in the application of these commercial tools without requiring specific development, in the case where the thermal structure is still affect by recent events.

Regarding the results obtained for LHVC model, it is important to highlight that the regional calibration of the thermal structure of LHVC was naturally obtained taking into account the available information, without the need of any particular artifact tuning . Knowledge obtained from previous studies concerning the age of the caldera stages and structure of the associated magmatic chambers were key to this study. The results shows that the overall thermal structure of LHVC is guided by these large scale intrusions. The higher temperatures observed at the western part of the section are related to the earlier Los Potreros caldera phase, that is restricted to this area.

Regarding the local thermal anomalies (e.g. in well H8), our first results indicated that they are probably related to localized small intrusive bodies. Nevertheless additional analyses will be carried out with TemisFlow® in order to investigate the possible effect of regional water circulation on the temperature heterogeneities.

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