MODELING NATURAL STEADY- STATE OF SUPER HOT GEOTHERMAL RESERVOIR AT LOS HUMEROS, MEXICO

Paromita Deb[1], Dominique Knapp[2], Christoph Clauser[1], Giordano Montegrossi[3]

[1] Institute for Applied Geophysics and Geothermal Energy, RWTH Aachen University (Germany),

[2] Geophysica Beratungsgesellschaft mbH, Germany

[3] C.N.R. –I.G.G.-U.O.S. Firenze (Italy)

pdeb@eonerc.rwth-aachen.de

Keywords: Los Humeros, super-hot reservoir, natural-state, numerical simulation, basal-heat flow

ABSTRACT

Within the framework of GEMex, a Horizon 2020 project (Grant Agreement No. 727550), we model the initial natural state of the super-hot reservoir system of Los Humeros. This is achieved by solving the porous flow and heat transport equations in a gridded, structural 3D model of Los Humeros using the SHEMAT-Suite (Simulator for Heat and Mass Transport) software (Rath et al., 2006, Clauser, 2003). Initially, we perform purely conductive simulations and check the simulated temperatures against the temperatures measured at the well bottoms. We tested several conductive scenarios to obtain an understanding of the pattern of the basal specific heat flow under the Los Humeros caldera complex.

1. INTRODUCTION

Los Humeros is the third largest geothermal field in Mexico in view of both installed capacity and electricity generation. It is a caldera complex situated in the eastern part of the Trans-Mexican Volcanic Belt (TMVB) at an elevation of approximately 2800m (Figure 1). The field is operated by Comisión Federal de Electricidad (CFE). The first exploration well was drilled in 1982 but the commercial exploitation began only in 1990. Having been in production for nearly 30 years, almost 123 million tonnes of fluids had been extracted from the reservoir until 2012 (Arellano, 2015). In spite of its long history, the geothermal system continues to pose complex challenges towards producing high-enthalpy super-critical fluids.

We construct a 3D numerical model by using an existing geometrical structure created within GEMex (Calcagno, 2018). The simulation domain comprises an area of 56 km × 36 km × 9.6 km with a total of six million grids cells. The geological structure includes a limestone basement, topped by several volcanic series and a number of caldera related fault systems. We analyse temperature and pressure data from more than 50 wells obtained during the drilling and completion stages and ancillary information owned by CFE. From this information, we reconstruct the pseudo steady-state temperature and pressure conditions at depth.

The complex tectonic history of the caldera system and the different conceptual ideas proposed by different researchers make it difficult to infer the boundary conditions required for the numerical model. In addition, the quite differing production behavior of wells located very close to each other suggests the existence of structural heterogeneity as well as variable heat source conditions at depth. This paper describes the workflow used for obtaining an initial estimate of basal specific heat flow conditions in spite of the lack of any a priori information on the dimension and depth of the heat source.

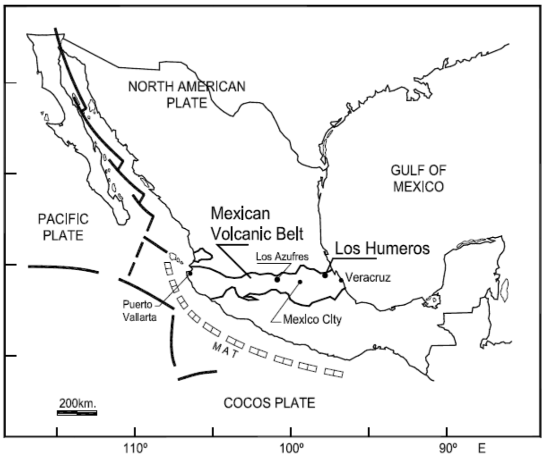

Figure 1: Regional tectonic setting of the TMVB and Los Humeros geothermal field (Arellano et al., 2003)

2. GEOLOGY

The Los Humeros caldera complex comprises of at least two main caldera forming phases, resulting in a nested caldera system. The main ideas about the evolution of this caldera system are explained by Ferriz and Mahood (1984). Geometrical modeling of the lithological units used for simulation is performed based on a geological map of Carrasco (2017) (Figure 2) and well data from CFE. The volcanic rocks are grouped lithologically based on drill cuttings, geochemical, and well data. The geothermal system rests on a limestone basement which is highly deformed and outcrops towards the northwest of the Los Humeros caldera (Carrasco, 2017). This basement is overlain by thick Miocene andesite sequences. The main feeding zones for this geothermal system are located within these andesitic units. In contrast, the highly impermeably ignimbrites formed during the caldera phases act as seals.

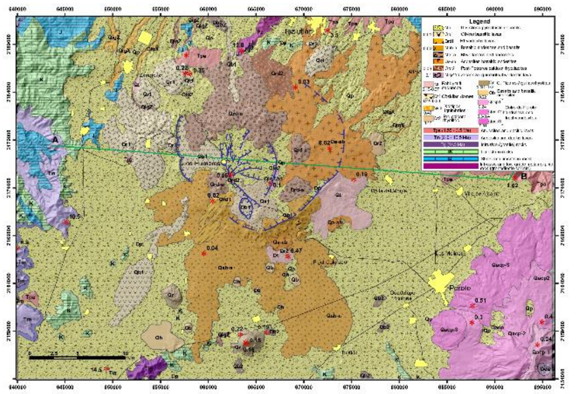

Figure 2: Geological map of the Los Humeros Caldera Complex (Carrasco-Núñez et al., 2017)

3. DETERMINING BASAL HEAT FLOW CONDITIONS

The average specific heat flow obtained from borehole data in the TMVB and Sierra Madre Oriental is 90 ± 16 mW m^{-2} (Ziagos et al., 1985). Other authors find the specific heat flow in the area to range between 75 mW m^{-2} and 83 mW m^{-2} (Pollack et al. 2010), or even 35 mW m^{-2} and 85 mW m^{-2} in the north of Los Humeros geothermal field (Davies, 2013). This high variability of the heat flow distribution observed on a larger scale can be explained by the complex setting of the continental trench-arc/back-arc system and the temperature perturbations associated with uplift, orogeny and erosion (Ziagos et al., 1985). As the Los Humeros Caldera is bordered in the east by the Cofre de Perote volcanic chain and in the west by the Sierra Madre Oriental high, we take the specific heat flow of 91 mW m^{-2} from Ziagos et al. 1985 as a regional specific heat flow background signal for the TMVB.

However, the extremely high temperatures observed in the geothermal wells within the Los Humeros caldera cannot be explained by a uniform regional specific heat flow of 91 mW m^{-2}. At a depth of around 2000 m – 2200 m, temperatures of the order 300 °C or higher are recorded in unproductive, very low-permeability wells.

Conceptual volcanological studies performed within GEMex question the existence of one single magma chamber below the caldera. Geochemical, geo-thermometric and geo-barometric data obtained from the superficial deposits of post-caldera units indicate a polybaric evolution of the Los Humeros magmas (Giordano et al., 2018). Against this background, we therefore test several scenarios with different possible heat distribution scenarios.

3.1 Conductive simulations on 2D cross sections

Figure 3 is a horizontal depth slice at 1500 m a.s.l. showing the modelled lithological units and fault systems. The Los Humeros and Los Potreros caldera faults are outlined. The wells shown in the map are the boundary wells of the geothermal field. It can be seen from the figure that almost all of these boundary wells are located within the big caldera system. Outside the caldera, there is almost no information regarding the temperature except from shallow (100 m - 200 m) water wells.

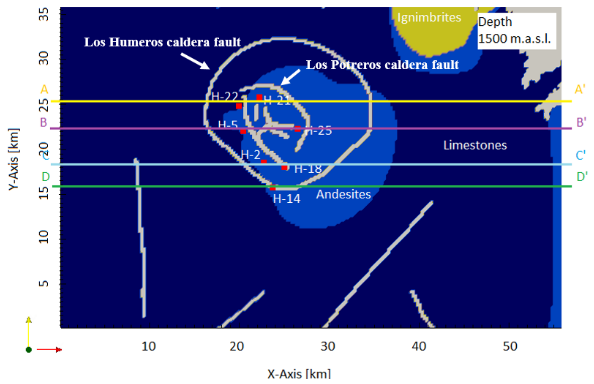

Figure 3: Depth slice from the regional model at 1500 m a.s.l. showing modeled rock units, Los Humeros and Los Potreros caldera faults, location of border wells H-22, H-5, H-2, H-14, H-18, H-25 and H-21, and four E-W cross-sections

In a first attempt, we consider four E-W oriented cross sections, A-A', B-B', C-C' and D-D' (Figure 3) and perform simulations based on the assumption of pure heat conduction. The regional specific heat flow outside of the Los Humeros caldera is assumed to be 91 mW m^{-2}. An estimate of the specific heat flow at the base of the domain was obtained by calibrating the simulation results using corrected static bottom-hole temperatures at the well locations. These are calculated from transient temperature data recorded during the drilling and completion stages of the wells. These temperatures are affected by drilling and mud circulation and, sometimes, also by inter-zonal flows. It is therefore important to correct these temperature data using appropriate methods. Horner's method for transient pressure test data (Horner, 1951) is most commonly used due to the apparent similarity between pressure and temperature build-up (Dowdle and Cobb, 1975). However it was suggested that Horner's analysis of temperature build-up always underestimates the static formation temperature (Dowdle and Cobb, 1975, Eppelbaum and Kutasov, 2006) and is justified only with certain basic assumptions.

The Horner method is described by equation [1]

$$T_{ws} = T_i - C \cdot \log\left(\frac{t + t_c}{t}\right), \quad [1]$$

where T_{ws} is the shut in temperature at time t, T_i is the stabilised formation temperature at infinite shut-in time and t_c is the mud circulation time.

In addition to Horner's method we use another method for estimating the undisturbed formation temperature. It is based on a conceptual model assuming of spherical radial heat flow at the bottom of the well. The mathematical model and the related assumptions are described in Ascencio (1994). The spherical radial heat flow method is based on equation [2]

$$T_{ws} = T_i - C\frac{1}{\sqrt{t}} \quad [2]$$

It is observed that the temperatures calculated from equation [2] are always greater than those obtained from Horner's method. Garcia-Gutierrez (2002) suggested that this method provides static temperatures that are closer to the true formation temperatures in the Los Humeros geothermal field.

In our study, however, we calculate static formation temperatures for each well using both methods. Temperatures calculated from equation [1] and [2] are used as lower and upper bounds, respectively, for comparison with simulation results extracted at each well position.

In our heat conduction simulations, the variation of thermal conductivity with temperature is accounted for using the relationship proposed by Sekiguchi (1984). It is considered to provide the best fit for the temperature dependency of igneous and metamorphic rocks to data in the temperature range from 0 °C to 500 °C (Lee and Deming, 1998). It accounts for the temperature dependence of matrix thermal conductivity λ_m based on a given matrix conductivity at room temperature $\lambda_{m,0}$ and the temperature T. We implemented it as suggested by Pasquale et al (2017):

$$\lambda_m = 1.8418 + (\lambda_{m,0} - 1.8418) \cdot \cdot \left(\frac{1}{0.002732\,T + 0.7463} - 0.2485\right) \quad [3]$$

Wells H-14 and H-25 are the most southerly and easterly wells, respectively, drilled within the Los Humeros caldera rim. Temperature logs measured over time appear purely conductive in these wells. CFE considers these wells as non-productive due to absence of any permeable zones at greater depth. Well H-5 which is westernmost well in the field also shows pure conductive trend in the temperature data.

We performed heat conduction simulations in the four E-W oriented cross-sections assuming numerous specific heat flows under the Los Humeros caldera. Figure 4 shows the temperature simulation for well H-14 for several of these basal specific heat flow scenarios extracted from simulation along cross-section D-D'. It can be seen that specific heat flow values between 225 mW m^{-2} and 250 mW m^{-2} provide a good temperature fit. The Horner-corrected bottom-hole well temperature for H-14 is plotted in the figure for comparison.

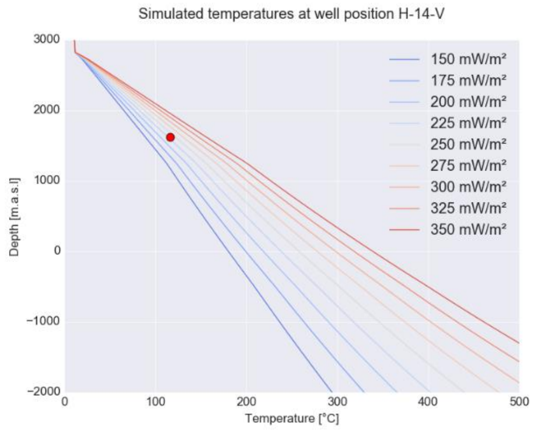

Figure 4: Simulated temperature for well H-14 by conductive simulation in 2D E-W cross section (D-D'). Red circle: Horner-corrected bottom-hole well temperature.

Results of conductive simulation along C-C' cross section (not shown here) indicated that well H-18, which is the most southerly well of Los Potreros caldera required a higher specific heat flow of the order of 275 mW m^{-2} - 300 mW m^{-2} in order to match the recorded bottom hole temperature. From cross-section B-B', temperature for the easternmost well H-25 is extracted, which shows a good match with temperature when simulated with a specific heat flow of around 225 mW m^{-2} – 250 mW m^{-2} .Well H-2 which is to the east of H-18 and separated by NW-SE oriented main faults could not be matched, even with basal specific heat flows as high as 350 mW m^{-2}. Similar results are obtained for wells close to the NW-SE oriented main fault, such as, H-5 and H-21. These results indicated the need of increasing the specific heat flow conditions under Los Potreros caldera.

3.2 3D conductive models

The 2-D heat conduction simulations indicate that a uniform specific heat flow under the caldera complex is insufficient for explaining the complex temperature pattern observed in the wells. The specific heat flow pattern observed in 2D cross-sections under different wells is influenced by the geometry and lateral variation of thermal rock properties when heat transfer processes occur in a 3D domain. Therefore, in a next step, the heat flow distribution is tested in 3D regional settings.

Our large regional model has dimensions of 56 km × 36 km × 12 km and reaches a depth of 7 km below mean sea level. The vertical extent of the model was limited to 4600 m below sea level for reducing the number of grid nodes as well as the uncertainty due to the lack of hard information at greater depth. We tested different heat conduction scenarios by varying the basal specific heat flow pattern under Los Humeros caldera and Los

Potreros caldera. Table 1 shows six different scenarios of the regional conductive model assuming possible specific heat flow configurations.

Figure 5 shows specific heat flow pattern in the model domain at 4600 m b.s.l. according to the values given in Table 1; the caldera and fault geometry are projected from 1500 m a.s.l. depth for visualisation purpose. Within the green boundary we assume the regional specific heat flow, within the orange and red rectangles the Los Humeros and Los Potreros caldera values, respectively. The region within the dark red rectangle in the north-eastern part of the Los Potreros caldera has the highest specific heat flow. Because the dimension as well as the depth of the heat source are unknown, this configuration, assigns to the base of our model a simple heat flow pattern increasing gradually from the value calculated at the TMVB (Ziagos et al., 1985) towards the Los Potreros caldera.

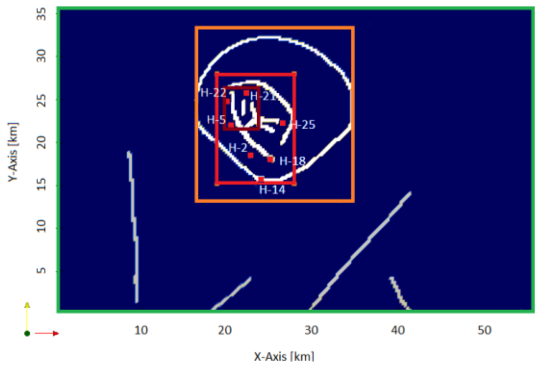

Figure 5: Specific heat flow pattern in the model domain at 4600 m b.s.l. Green boundary: regional specific heat flow; within orange and red rectangles: the Los Humeros and Los Potreros caldera values, respectively. Within the dark red rectangle, the highest specific heat flow in the Los Potreros caldera (Table 1).

Table 1: Heat flow scenarios for testing basal specific heat flow conditions in the regional model

Scenario	Regional specific heat flow [Wm⁻²]	Los Humeros caldera [Wm⁻²]	Los Potreros caldera [Wm⁻²]	North-eastern part of Los Potreros caldera [Wm⁻²]
Scenario 1	0.091	0.175	0.225	0.225
Scenario 2	0.091	0.175	0.250	0.250
Scenario 3	0.091	0.175	0.250	0.350
Scenario 4	0.091	0.200	0.250	0.250
Scenario 5	0.091	0.200	0.300	0.300
Scenario 6	0.091	0.200	0.300	0.450

4. RESULTS AND DISCUSSION

Figure 6 presents the comparison of different heat conduction scenarios along cross section B – B' (Figure 3), which crosses H-5 and H25. With increasing specific heat flow from Scenario 1 to Scenario 3, isotherms are uplifted towards the caldera floor. Between Scenario 1 and Scenario 5, for example, the uplift of the 500 °C isotherm is about 1 km.

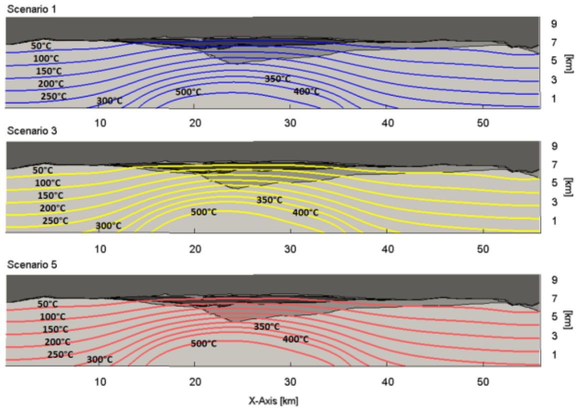

Figure 6: Comparison of isotherms for the B-B' cross-section for different scenarios of 3D heat conduction simulations

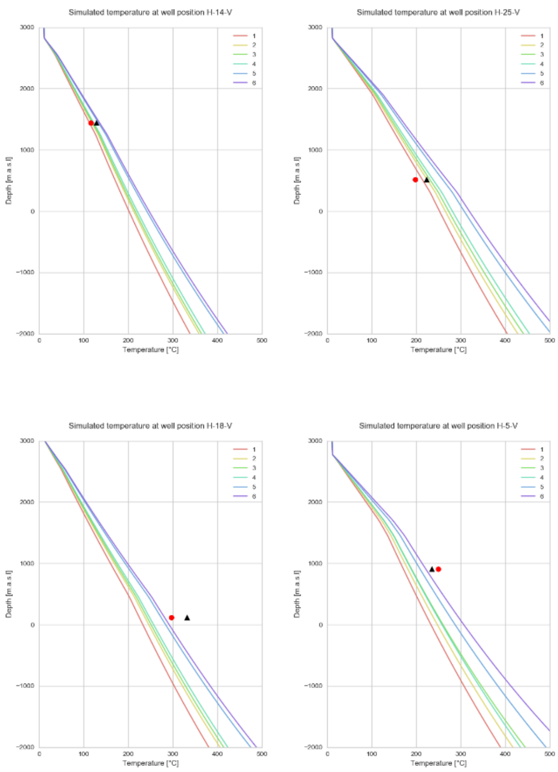

Figure 7: Simulated temperatures extracted for different conductive scenarios (top H-14 left, H-25 right; bottom H-18 left, H-5 right). Red circle and black triangle: bottom-hole well temperature corrected according to equations [1] and [2], respectively.

Figure 7 shows the simulated temperatures extracted for wells H-14, H-18, H-25 and H-5 for the different scenarios presented in Table 1. Bottom-hole well temperatures corrected according to equations [1] and [2] are indicated by red circles and black triangles, respectively. At the reservoir level (1500 m a.s.l.) of well H-14, the different scenarios yield a spread in temperature on the order of 21 K. With depth the difference in resulting temperature increases for the different scenarios. But overall, a basal specific heat flow as high as 200 mW m^{-2} used in Scenario 4 and 5 under the Los Humeros Caldera seems appropriate.

The most easterly well of the Los Potreros caldera, H-25, requires a basal specific heat flow of the order of 225 mW m^{-2} – 250 mW m^{-2} for an acceptable match with the well data.

In contrast, the simulated temperatures of wells H-18 and H-5 could not be matched by any of the above configurations. Well H-5 shows a conductive trend in the temperature logs, and the drilling data show no indication of circulation losses at greater depth. Wells H-21 and H-22, located in the northeastern part of Los Potreros caldera, cannot be matched even with a very high basal specific heat flow of the order of 450 mW m^{-2} (Scenario 6).

These results require a different explanation beyond a pure heat conduction scenario which cannot explain all the temperatures observed in different wells: Apparently, heat transfer occurs also by advection. The faults of the caldera complex and the associated fractures dominate the heat transfer wherever the formation is permeable. This is one likely cause of the very high temperatures observed in some of the wells.

On the other hand, the presence of a localized shallow heat source of smaller dimension possibly formed by local intrusions towards the north-east of Los Potreros might be another possible explanation for the very high temperature observed in the low permeable wells of this area. In summary, the idea proposed in previous studies of one single magma chamber cooling underneath the Los Humeros and Los Potreros calderas, is seriously challenged by our analysis.

5. CONCLUSION

Heat conduction simulations confirm the fact that this process alone is insufficient for explaining the temperatures observed in all of the wells. Therefore, it is necessary to include heat advection as a second heat transfer process in future simulations. For this purpose, the hydraulic properties of the structural elements need to be known with sufficiently small uncertainty. The depth and geometry of the deep annular faults of the caldera complex and their sealing conditions determine the recharge conditions in the reservoir. High-resolution geophysical studies are necessary to map these structures and their geometry.

This study will be followed up by a model accounting for heat advection in addition to conduction as a heat transfer process within the Los Potreros and Los Humeros calderas. Additionally and equally important, the role of the fault network for the observed conditions in the current production wells will be studied.

REFERENCES

Arrelano, V. M., García, R.M., Barragán, G., Izquierdo, A., Araagón, A., Nieva, D., 2003. An updated conceptual model of the Los Humeros geothermal reservoir (Mexico), *Journal of Volcanology and Geothermal Reserarch* , 124, 67- 88.

Arellano, V. M., Barragán, R. M., Ramírez, M., López, S., Paredes, A., Aragón, A., Tovar, R., 2015. The Response to Exploitation of the Los Humeros (México) Geothermal Reservoir. *Proceedings World Geothermal Congress 2015,* Melbourne, Australia.

Ascencio, F., Garcia, A., Rivera, J. and Arellano, V., 1994. Estimation of undisturbed formation temperatures under spherical-radial heat flow conditions. *Geothermics, 23, 4, 317-326*

Clauser, C., ed., 2003. Numerical Simulation of Reactive Flow in Hot Aquifers SHEMAT and PROCESSING SHEMAT, *Springer*, New York.

Calcagno, P., Evanno, g., Trumpy, E., Gutiérrez-Negrín, L. C., Macías, J. L., Carrasco-Núñez, G., Liotta, D., 2018. Preliminary 3-D geological models of Los Humeros and Acoculco geothermal fields (Mexico) – H2020 GEMex Project., *Advances in Geosciences, 45,* 321 – 333.

Carrasco-Núñez, G., López-Martínez, M., Hernández, J., Vargas, V., 2017. Subsurface stratigraphy and its correlation with the surficial geology at Los Humeros geothermal field, eastern Trans-Mexican Volcanic Belt, *Geothermics,* 67, 1 – 17.

Davies, J. H., 2013. Global map of solid Earth surface heat flow. *Geochem. Geophys. Geosyst. 14,* 4608 – 4622.

Dowdle, W. L. and Cobb, W.M., 1975. Static formation temperature from well logs – an empirical method, Journal *of Petroleum Technology*, 27 (11), 1326-1330

Eppelbaum, L.V. and Kutasov, I.M., 2006. Determination of formation temperatures from temperature logs in deep boreholes: comparison of three methods, *Journal of Geophysics and Engineering*, 348 – 355

Ferriz, H. and Mahood, G.A. 1984. Eruption rates and compositional trends at Los Humeros Volcanic Center, Puebla, Mexico. *Journal of Geophysical Research 89(B10),* 8511–8524, *doi: 10.1029/JB080i010p08511.*

García-Gutiérrez, A., Arellano, V., Barragán, R.M. Espinosa-Paredes, G. 2002, Initial temperature field in the Los Humeros geothermal reservoir, *Geofisica International*, Vol. 41, Num 3, pp. 303-312

Giordano G., Lucci F., Rossetti F., Urbani S. 2018, Update on the volcanological conceptual model of Los Humeros geothermal field, *3rd GEMex Meeting*, Morelia

Horner D. R., 1951. Pressure buildup in wells, in *Proceedings of Third World Petroleum Congress*, Section II, The Hague, Netherlands, 28 May – 6 June.

Lee, Y., Deming, D., 1998. Evaluation of thermal conductivity temperature corrections applied in terrestrial heat flow studies. *Journal of Geophysical Research*, 103(B2), 2447 – 2454.

Pollack, H. N., Hurter, S. J., Johnson, J., R., 2010. Heat flow from the earth's interior: Analysis of the global data set. *Review of Geophysics, 31,* 267-280.

Rath, V., Wolf, A., Bücker, H. M., 2006. Joint three-dimensional inversion of coupled groundwater flow and heat transfer based on automatic differentiation: sensitivity calculation, verification, and synthetic examples, *Geophys. J. Int. 167***,** 453–466, doi: 10.1111/j.1365-246X.2006.03074.x

Sekiguchi, K., 1984. A method for determining terrestrial heat flow in oil basin areas. *Tectonophysics, 103,* 67 – 79, Elsevier Science Publishers B. V. Amsterdam - Netherlands

Ziagos, J. P., Blackwell, D. D., Mooser, F., 1985. Heat Flow in Southern Mexico and the Thermal Effects of Subduction. *Journal of Geophysical Research, 90,* 5410 – 5420.

Acknowledgements

The author thanks the Comision Federal di Electricidad (CFE) for providing data and information regarding their geothermal wells and the entire GEMex consortium comprising of Mexican and European partners for the cooperation and unpublished inputs on conceptual ideas which are used for this study.