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Continental heat flow data update for México – Constructing a reliable and accurate heat flow map

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ABSTRACT

México has a large potential of high enthalpy geothermal resources, as shown by existing geothermal fields in exploration and exploitation for power generation. In addition, a large number of sites containing thermal manifestations have been considered as low and medium enthalpy, and could be proposed for utilization in direct uses of geothermal energy. However, the direct use of geothermal systems in México is not developed. Some of the poorly studied or explored sites that are considered as low or medium enthalpy might have the potential to generate electricity; therefore, the Mexican Centre for Innovation on geothermal energy (CeMIE-Geo) has launched a campaign of geothermal exploration projects in various parts of the country, including a project for regional evaluation of geothermal potential and definition of the geothermal provinces.

One important stage of regional exploration includes the characterization of the thermal regime related with heat transfer from the deep parts of the crust toward the surface. The thermal regime is defined by the surface heat flow and the geothermal gradient; therefore, here we present the results of the CeMIE-Geo project that aims to developing maps of heat flow and geothermal gradient, in order to assess the geothermal resources of the country and to help locating possible favorable areas for exploitation.

In this work 724 heat flow data were compiled to integrate a new database, which consists of 517 published and 207 new data [108 recently published by Espinoza-Ojeda et al (2017) and 99 new data]. The new heat flow data were calculated with temperature logs [Borehole Transient Temperature (TBT) and Bottom-Hole Temperature (BHT)] from geothermal and oil exploration wells. This new database contains sites mostly in northern México. It is valuable to define areas with thermal anomalies and classify areas with low, medium and high enthalpy geothermal resources according to the observed heat flow values.

1. INTRODUCTION

The knowledge of the current thermal state of the lithosphere helps us to better understand its influence on geophysical and geological processes, as well as rock properties and the thermal evaluation of geothermal systems. The most reliable data we could obtain are continental heat flow measurements, for the most accuracy and a better understanding of the lithospheric thermal regime.

Although many high-enthalpy geothermal resources in México have already been discovered and exploited (e.g. Gutiérrez-Negrín, 2015; Gutiérrez-Negrín et al., 2015), medium and low enthalpy resources are far more abundant (e.g. Iglesias et al., 2011, 2015). Their exploitation depends on a good knowledge of the geothermal potential in México. This knowledge is hampered by a lack of high quality heat flow measurements.

The lack of heat flow measurements in México have led to indirect methods for estimating the thermal regime. The most common indirect methods include using helium isotopic concentrations of local gases measured in thermal springs and the analysis of geothermal fluids through silica geothermometry to estimate reservoir temperature. However, these methods have relative uncertainties of approximately ±10 °C (e.g. Elders et al., 1984; Prol-Ledesma and Juarez, 1985; Prol-Ledesma, 1991; Barragan et al., 2001; Beltran-Abaunza and Quintanilla-Montoya, 2001; Arango-Galván et al., 2011). Another indirect method is based on the Curie temperature (approximately 580 °C for magnetite) determination through the spectral analysis of aeromagnetic anomalies (e.g. Flores-Márquez et al., 1999; Chávez et al., 2000; Espinosa-Cardeña and Campos-Enriquez, 2008; Manea and Manea, 2011; Rosales-Rodríguez et al., 2014).

Previous geothermal studies provide evidence about the location of low, medium and high enthalpy geothermal systems suitable for exploitation/utilization (e.g. Ziagos et al., 1985; Prol-Ledesma and Juarez, 1986; Arango-Galván et al., 2015; Gutiérrez-Negrín et al., 2015; Iglesias et al., 2015).

The purpose of the study is to update and expand the heat flow database for México to develop a better understanding of México's potential from the perspective of geothermal energy. New heat flow estimates from 207 sites are combined with published continental heat flow measurements to update the geothermal database in México (e.g. Smith, 1974; Smith et al., 1979; Von Herzen, 1963, 1964).

2. METHODOLOGY

The Comisión Federal de Electricidad (CFE) and Petróleos Mexicanos (PEMEX) provided us with geological and thermal geophysical information regarding 227 boreholes (including 20 off-shore sites). These boreholes are located predominantly along the Baja California Peninsula, the north central, northeast and central areas of México (Figure 1).

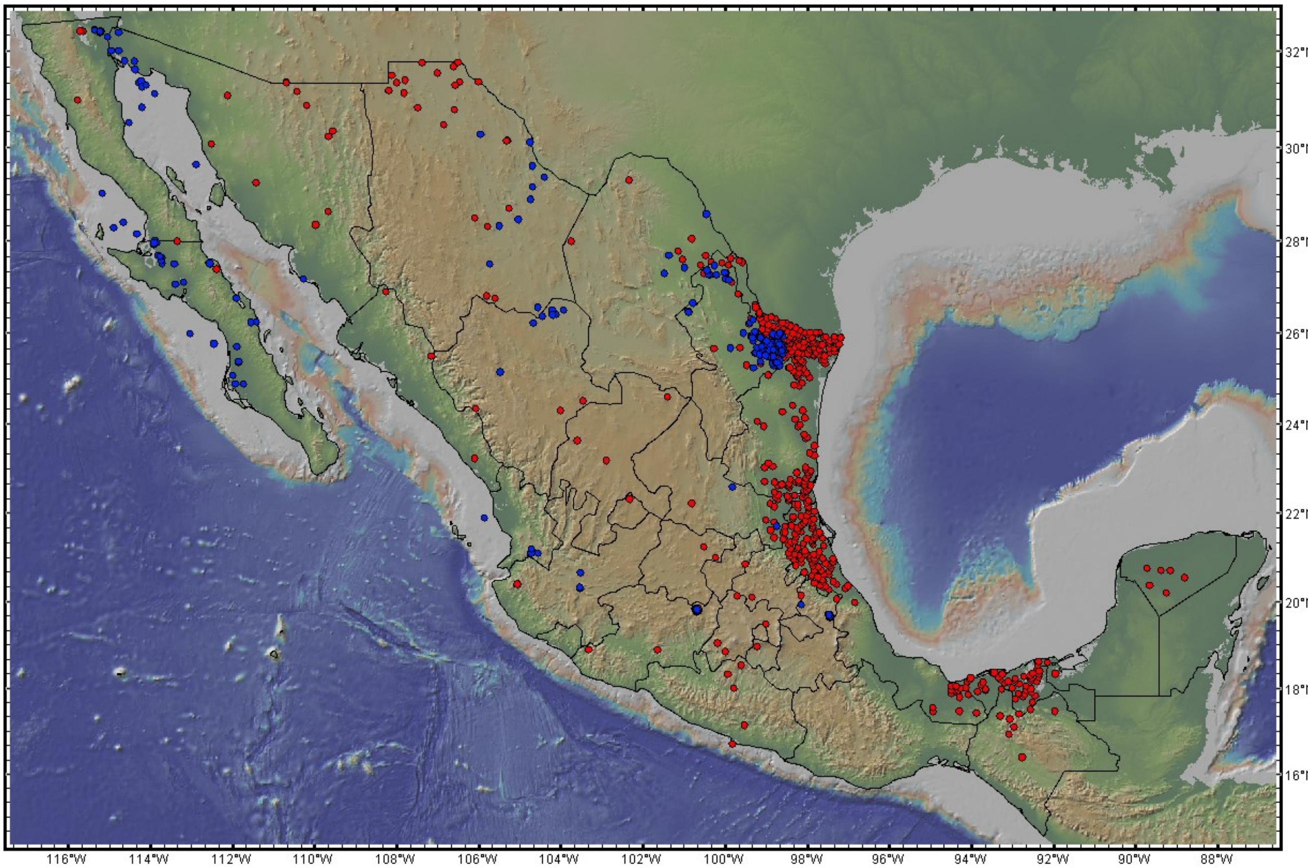

Figure 1: The updated heat flow data base: Blue (new heat flow sites: including the 108 sites recently published by Espinoza-Ojeda et al., 2017); Red (all compiled continental sites: other authors cited in this work).

To calculate the new heat flow data for the 207 continental boreholes, a fundamental methodology was proposed (Espinoza-Ojeda et al., 2017). Basically, the methodology consists of the following tasks:

(1) Create a Mexican database from the transient borehole temperatures (TBT) and bottom-hole temperatures (BHT) measurement logs of drilled boreholes. The database specifically consists of TBT and BHT data sets logged from 76 geothermal and 131 petroleum boreholes, respectively.

(2) Create the temperature-depth profiles from each borehole through the numerical treatment of the TBT and BHT data sets. Then, create a stratigraphic profile database according to the geological reports published by CFE and PEMEX.

(3) Calculate the conductive surface heat flow from each analyzed site using the Bullard method (Bullard, 1939).

Below, we provide a detailed description of the methodology.

2.1 Transient Borehole Temperatures (TBT) and Bottom-Hole Temperatures (BHT)

Temperature-depth data consist of either thermal recovery data log, which are also known as transient borehole temperatures logs (TBT), or bottom-hole temperatures (BHT). All boreholes used in this study exceed 100 m in depth (Figure 2); they also must have at least three temperature-depth measurements (Figure 3) and a full description of stratigraphic composition (Figure 4).

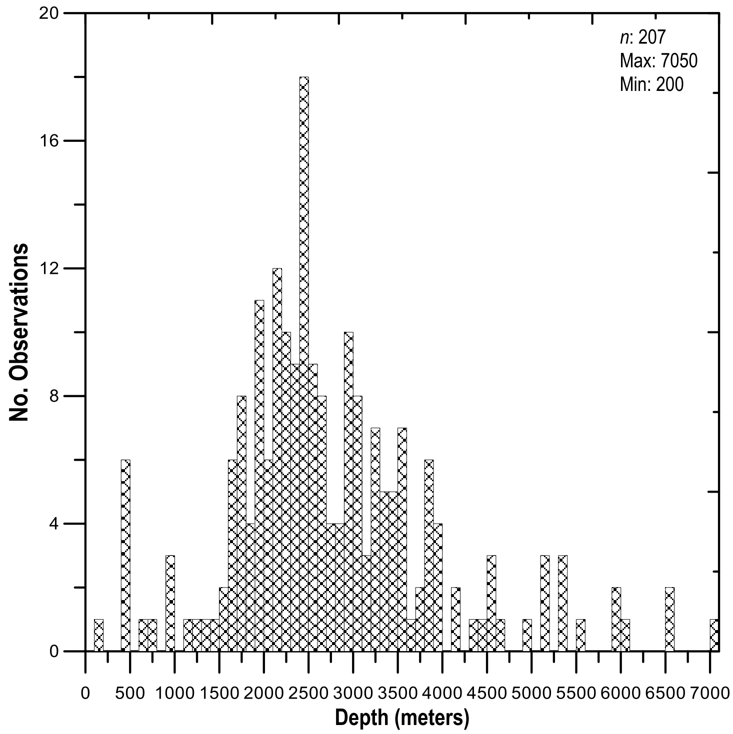

Figure 2: Histogram plot of the total depth from the selected 207 boreholes in this study.

TBT and BHT are generally measured directly after drilling and before the borehole has returned to thermal equilibrium conditions. TBT data consist of temperature, depth, and the elapsed time since circulation stopped, which is known as the shut-in time. Shut-in times are commonly up to 24 or 36 hours in the geothermal or oil industry (e.g., Kutasov, 1999; Figure 3). BHT is referred to as the temperature measured or logged at the bottom of the borehole that is reached at different depths during the drilling process (Figure 3). These temperatures are thought to be closer to equilibrium temperature because they are less influenced by the circulating fluids (e.g., Kutasov and Eppelbaum, 2010; Bonté et al, 2012; Zare-Reisabadi et al, 2015; Liu et al, 2016).

TBT measurements were used to estimate the stabilized formation temperature (SFT) for each borehole depth as described in Espinoza-Ojeda et al. (2011); then, this data was used to estimate geothermal gradients. As example for analyzing TBTs by illustrating the thermal analysis for the well MEX0044, which is located in central México. Borehole MEX0044 has 7 TBT measurements collected at four different depths (Figure 3). Shut-in times are up to 36 hours. Espinoza-Ojeda et al. (2011) investigated seven analytical methods for estimating SFT, these methods are derived from different heat transfer models that describe the thermal recovery process after drilling in geothermal and petroleum fields.

BHT data measured in oil and gas well log headers represent a measurement of the temperature of the drilling fluid in a borehole, which is generally cooler than the SFT in the bottom of the well. Therefore, the BHT measurements constitute a low quality set of temperature measurements commonly used in geothermal studies (e.g., Reiter and Tovar, 1982; Blackwell and Richards, 2004). Some BHT data are corrected using mathematical models that consider the effect of depth. In this context, Kehle et al. (1970) and Harrison et al. (1983) proposed empirical correlations that suggested a general depth dependent relationship to estimate the SFT from BHT data when only depth measurements are known with the objective of calculate the geothermal gradient map of North America. Then, similar to the previously mentioned works, Deming (1989) published one of the best known empirical corrections, which was proposed and is used by the American Association of Petroleum Geologists (AAPG). The AAPG correction was used to derive an average geothermal gradient correction as a function of depth. The temperature correction can be expressed as follows:

$$\Delta T = (1.878 \cdot 10^{-3})z + (8.476 \cdot 10^{-7})z^2 - (5.091 \cdot 10^{-11})z^3 - (1.681 \cdot 10^{-14})z^4 \qquad (1)$$

where ΔT is the temperature correction in °C, and z is the depth in meters. Equation (1) was used to correct the BHT data compiled for this work (e.g., Figure 3b).

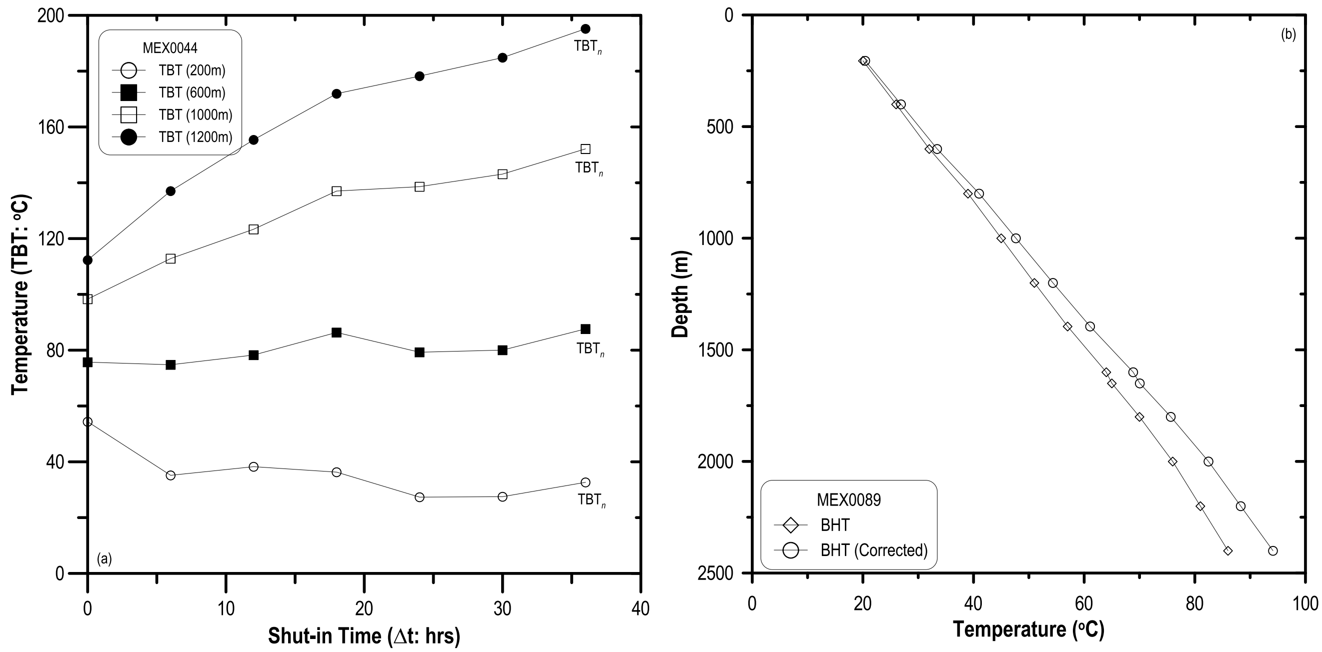

Figure 3: (a) Plots of the transient borehole temperature (TBT) from the MEX0044 borehole. Last measured Transient Borehole Temperature (TBTn). (b) Plot of the Temperature-Depth profile (measured BHT) from the MEX0089 oil borehole and its corresponding corrected BHT, according to Equation (1).

2.2 Conductive Surface Heat Flow

Once the temperatures were corrected, the temperature-depth profiles were constructed, and their corresponding rock formation stratigraphy were analyzed (Figure 4). Hence, to estimate the surface heat flow values, the Bullard plot method was applied to every temperature-thermal resistance relationship obtained from the available temperature-depth-rock formation data (e.g., Figure 5).

Measured values of thermal conductivity from these boreholes are not available, so we estimated thermal conductivities from catalogues of values (Jessop, 1990; Clauser and Huenges, 1995; Beardsmore and Cull, 2001) and the reported lithology of each borehole (Figure 4).

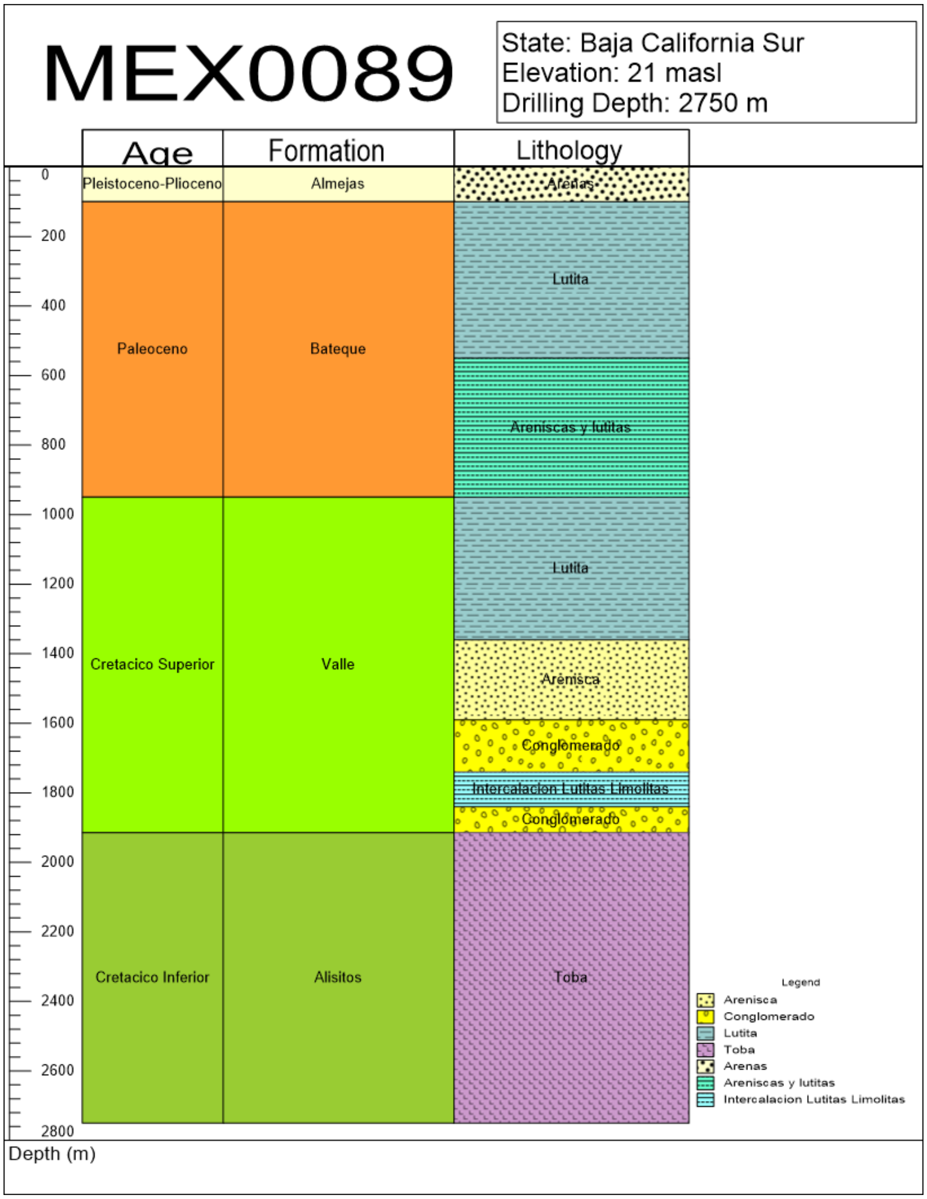

Figure 4: Description of the lithology from the borehole MEX0089. Arena (Sand), Lutita (Shale), Arenisca (Sandstone), Conglomerado (Conglomerate), Toba (Tuff).

To estimate heat flow in the presence of thermal conductivity variations, we use the Bullard method (Bullard, 1939):

$$T(z_i) = T_0 + q_0 R_i \tag{2}$$

where $T(z_i)$ is the temperature available at any given depth, T_0 is the surface temperature intercept, q_0 is the heat flow (HF), and R is thermal resistance that can be expressed as

$$R_i = \sum_i^n \frac{\Delta z_i}{k(z_i)} \tag{3}$$

where $k(z_i)$ is the thermal conductivity over the ith depth interval, Δz_i, and the summation is performed over n depth intervals from the surface to the depth of interest z. In practice, q_0 and T_0 are estimated by plotting $T(z_i)$ against the summed thermal resistance. As illustrative example, Figure 5 shows temperatures as a function of thermal resistance.

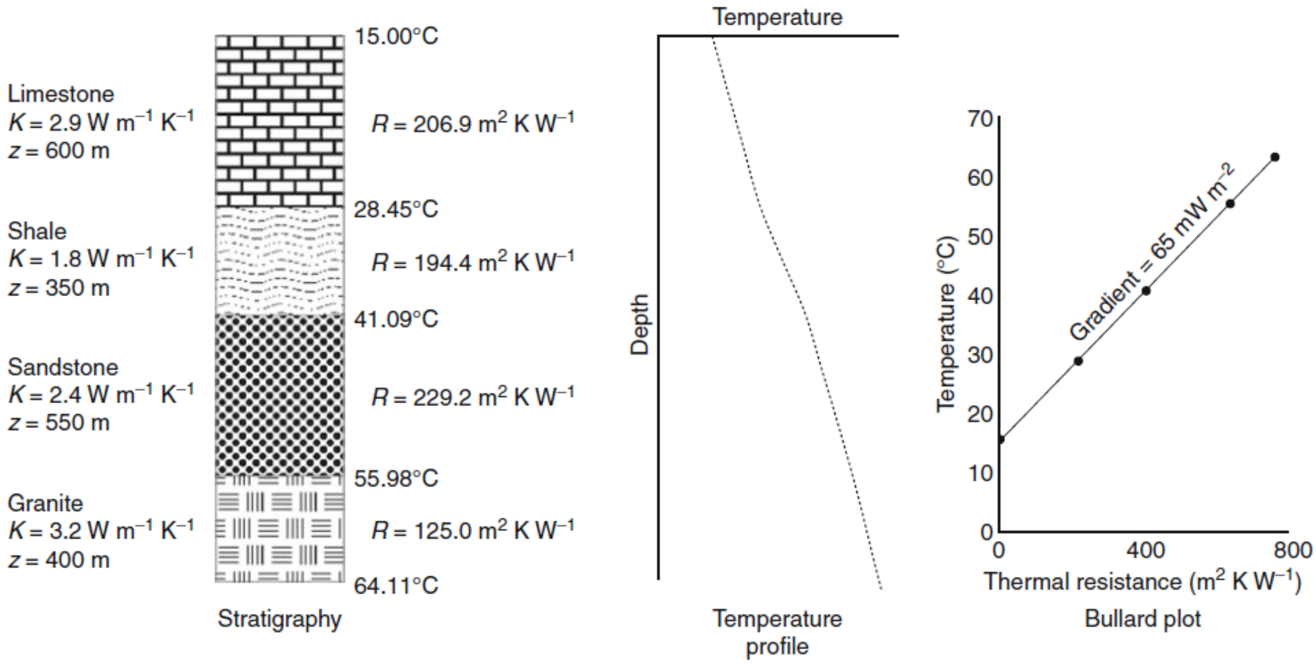

Figure 5: Illustrative example of the Bullard method to estimate conductive surface heat flow. Including the main components: Stratigraphy or rock lithology profile; the Temperature-Depth profile; and the Bullard plot (taken from Sass and Beardsmore, 2011).

3. NEW AND COMPILED HEAT FLOW DATA FROM MÉXICO

We compiled published and unpublished heat flow data in México, from conductive and non-conductive systems, to better define different heat flow zones in a map. Published data sources consulted include the following papers: Smith (1974); Lee and Henyey (1975); Smith et al. (1979); Reiter and Tovar (1982); Ziagos et al. (1985); Flores-Márquez et al. (1999); Chavez et al. (2000); García-Estrada et al. (2001); Blackwell and Richards (2004); Wilhelm et al. (2005); IHFC (2011); Lorenzo Pulido et al. (2011); and Espinoza-Ojeda et al. (2017).

Figure 1 shows the location of heat flow data in México. The distribution of the 207 new heat flow sites that have resulted from the compiled thermal data are shown (blue filled circles). The red filled circles describe the location of the published continental heat flow sites. From Figure 1, new data are mainly located within the Baja California peninsula as well as within the center, central-north, northeast and southeast of México.

Calculated (new) and overall compiled geothermal gradient and heat flow values are summarized in histogram plots (Figure 6 and 7, respectively). Figure 6 and 7 illustrate the ranges of most values. The histogram plots in Figure 6 and 7 present the large variation of values in the new and overall compiled geothermal gradient and heat flow data. These data show a statistical non-normal distribution, which is produced by the combination of stable and thermally perturbed conductive systems. As illustrative reference to the last claim and observations in Figure 6 and 7, preliminary heat flow maps were developed (Figure 8-11).

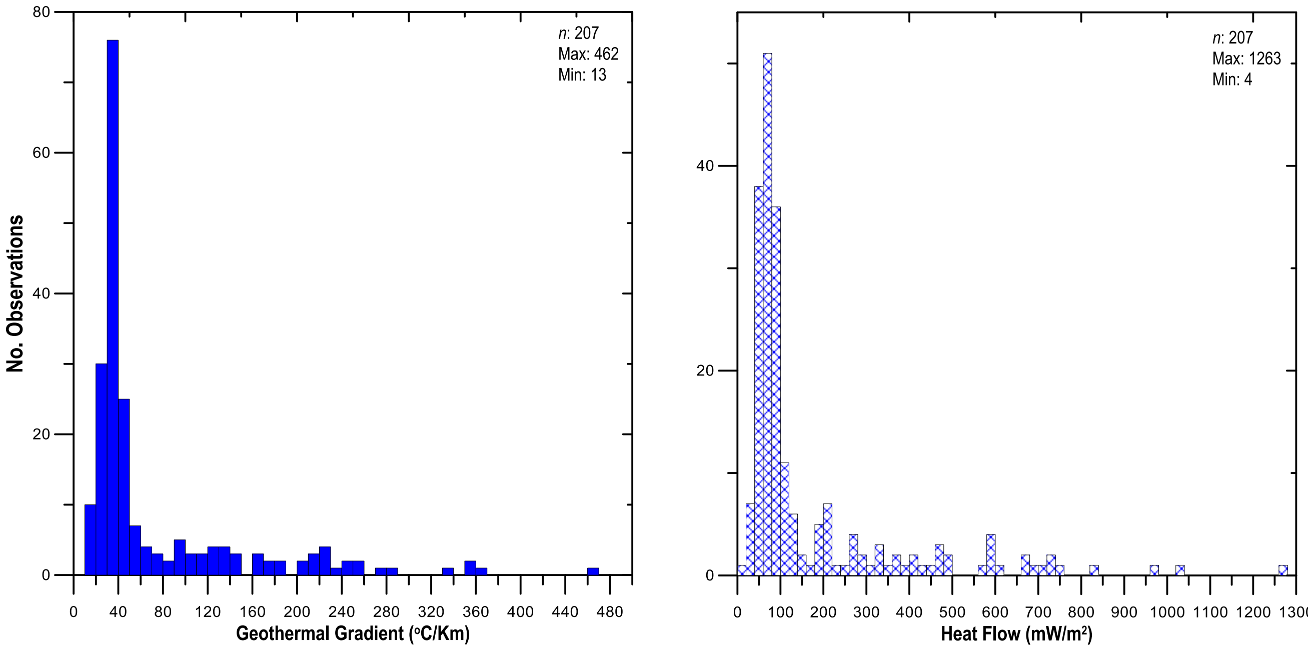

Figure 6: Histogram plots of the new geothermal gradient and heat flow calculations from Mexico. The plots include the number of data (*n*), and the maximum and minimum numerical values.

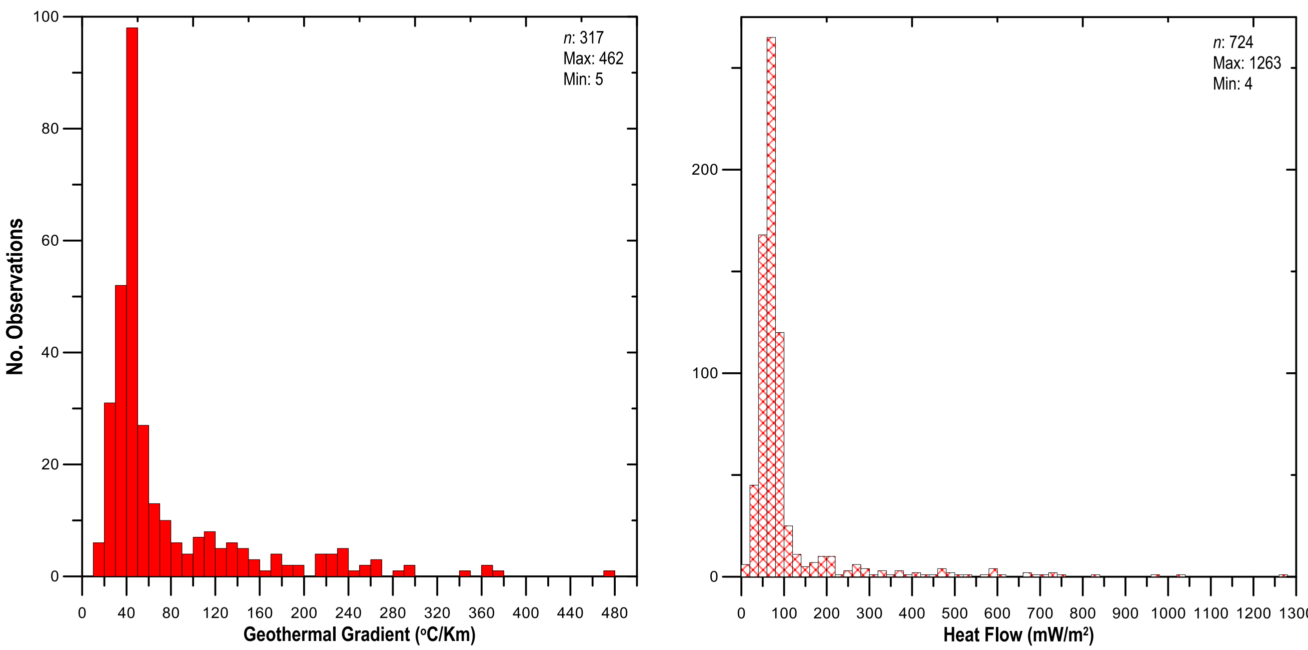

Figure 7: Histogram plots of the overall geothermal gradient and heat flow measurements from Mexico. The plots include the number of data (*n*), and the maximum and minimum numerical values.

Due to the non-uniform distribution of the continental heat flow observations in México (see Figure 1 and 7), there are large areas with no heat flow sites or large distances between each of the heat flow sites (except eastern México, along the Gulf of México coast). The updated heat flow data were divided in four sections (or zones) with the objective to aid visualization of the location and distribution of the data presented in Figure 7. Also, this helps to distinguish the location of the low, medium and high enthalpy geothermal sites, and it helps to characterize with a high accuracy or confidence level the actual thermal status of the proposed particular zones. These zones were proposed as follows: Northwest (Figure 8); Central-North (Figure 9); Northeast (Figure 10); and Southeast (Figure 11).

The 207 newly estimated heat flow values are between 4 and 1263 mW/m^2, and most heat flow values cluster within the range 40-120 mW/m^2. The compilation, review, and analysis of the published thermal data, including the new data, applied to the continental zone of México is shown in Figure 7, where all 724 heat flow values vary within the same range from 4 to 1263 mW/m2, and most values are between 20-200 mW/m2. This indicates that high enthalpy (> 120 mW/m^2; e.g., Chapman and Rybach, 1985; Chapman, 1986; Hasterok and Chapman, 2007) sites are rather uncommon in comparison with low and medium enthalpy zones. Figure 8 contains a map with the heat flow contour (or isotherm) data that correspond to the Northwest of Mexico, where we can observe that values are between 20 and 400 mW/m^2. Data along the Baja California peninsula have values between ≈40 and 70 mW/m^2 and are generally consistent with previously published values (Smith, 1974). Medium and some high enthalpy sites are located in central-north (Figure 9) and northeastern México (Figure 10). Low enthalpy heat flow sites are located mainly in southern México (Figure 11). Few are in the northern areas, and some others are concentrated in eastern México (Figure 9 and 10). The values greater than 120 mW/m^2 are located mainly inside/around the known Mexican geothermal fields. Those heat flow values are influenced (perturbed) by the energy sources related with the hydrothermal fields. Therefore, this confirmed that high and very high heat flow sites, located mainly along central México and Baja California peninsula, correspond to the largest geothermal fields (see Figure 8). The data with significant thermal perturbation (cooling or warming) resulting in low or high heat flow values might be greatly influenced by deeper thermal phenomena. This result supports the broad concept that very high enthalpy systems are infrequent but are scattered in wide areas in México (see Figure 7).

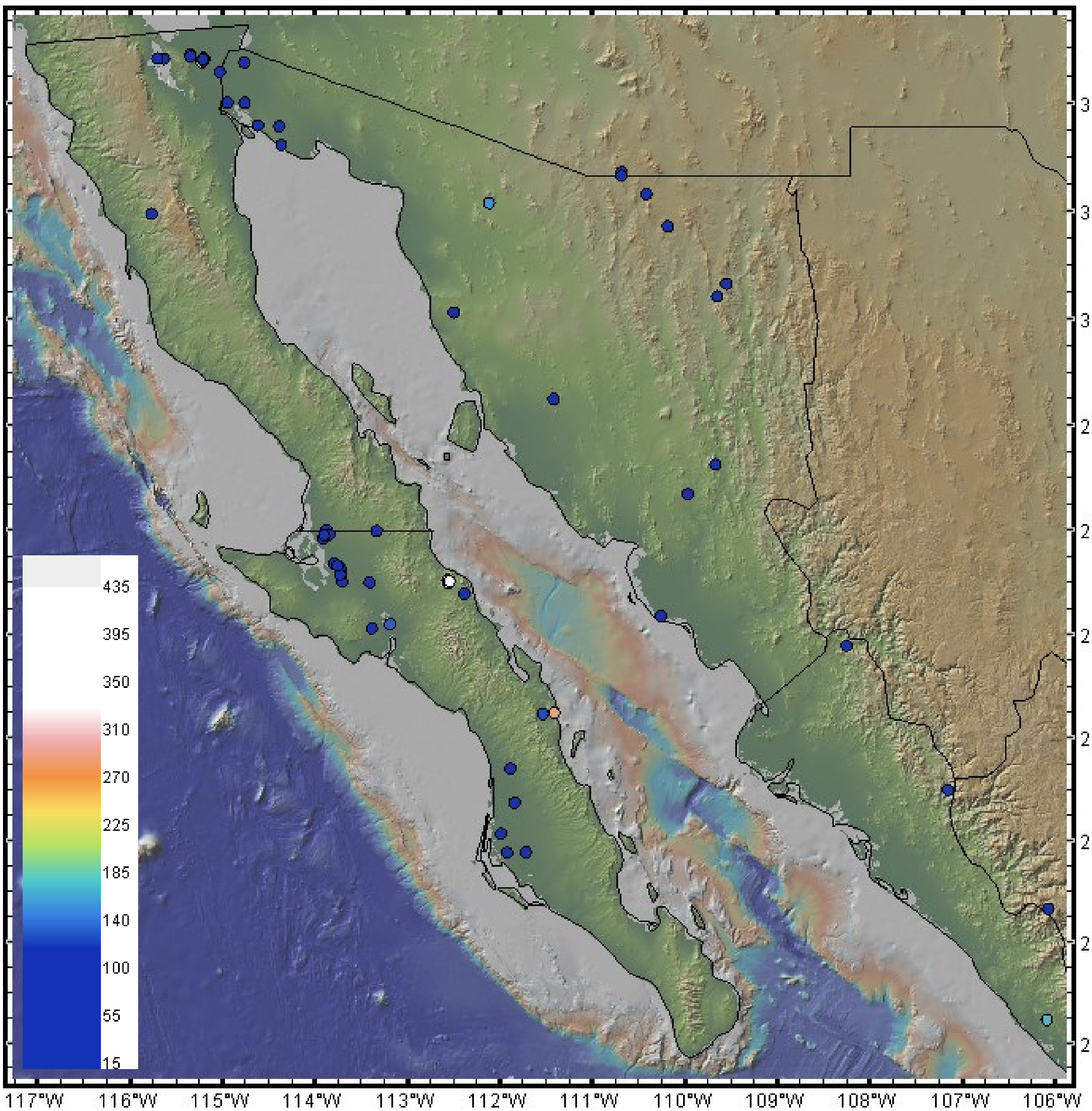

Figure 8: Northwest heat flow map of México.

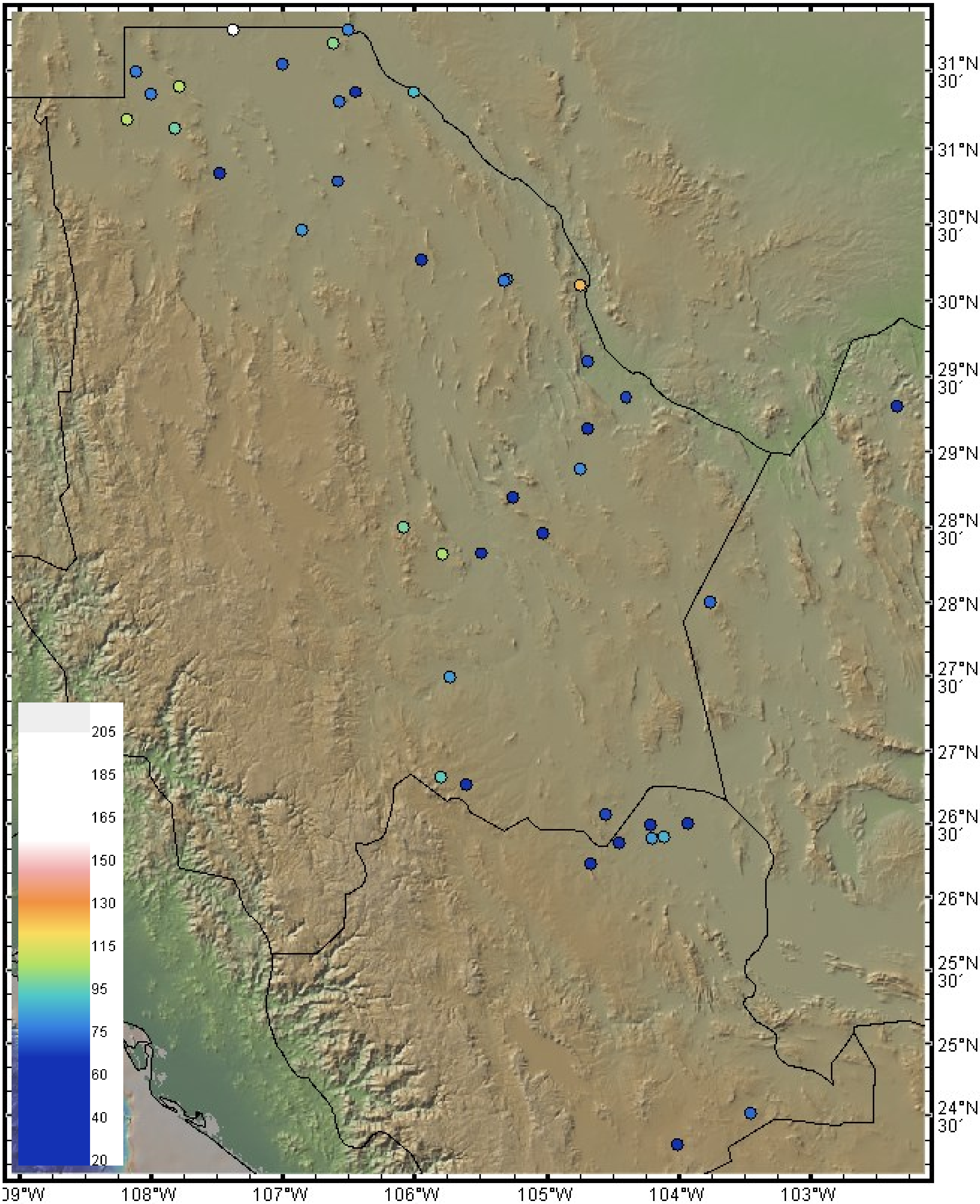

Figure 9: Central-North heat flow map of México.

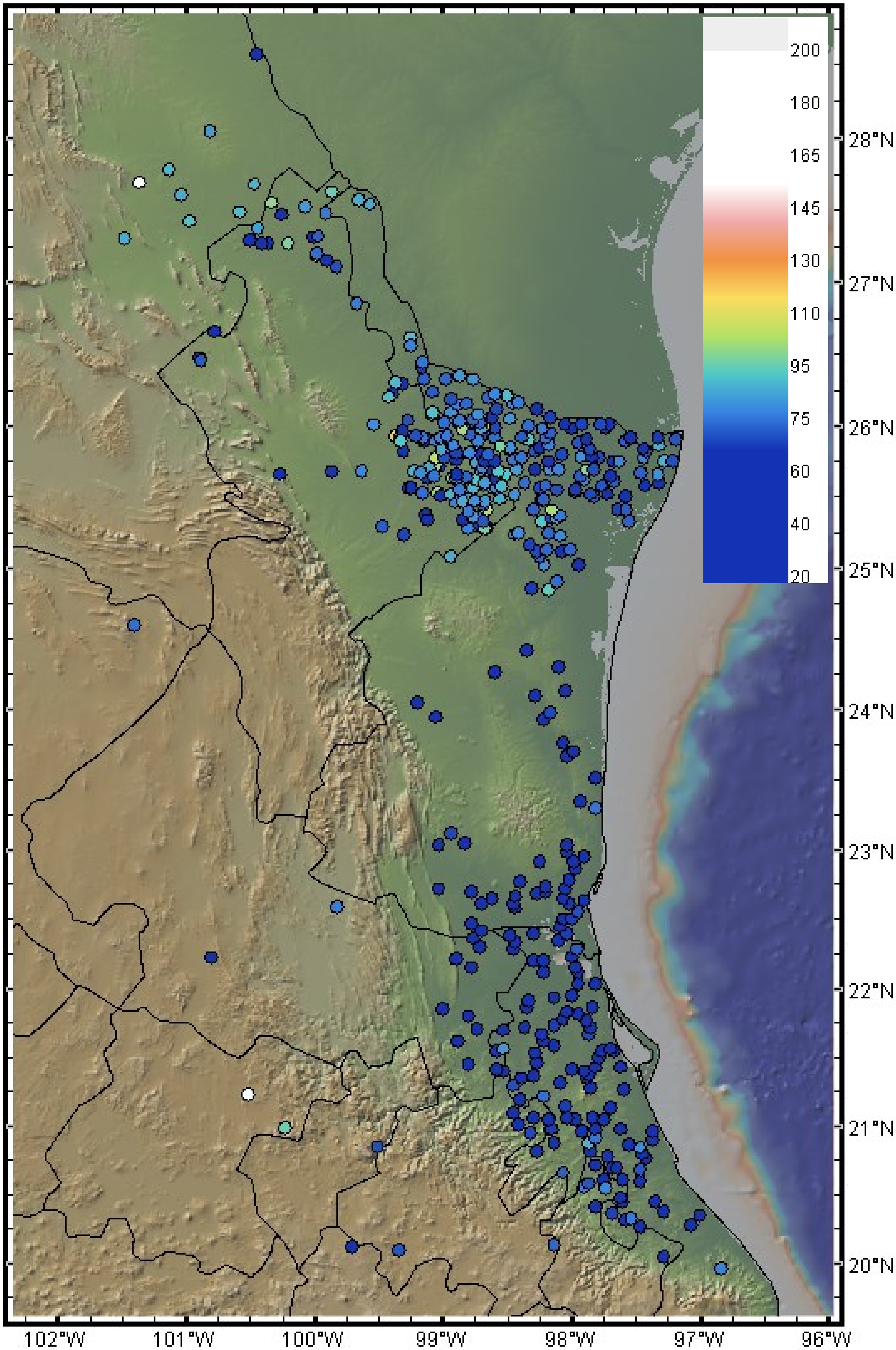

Figure 10: Northeast heat flow map of México.

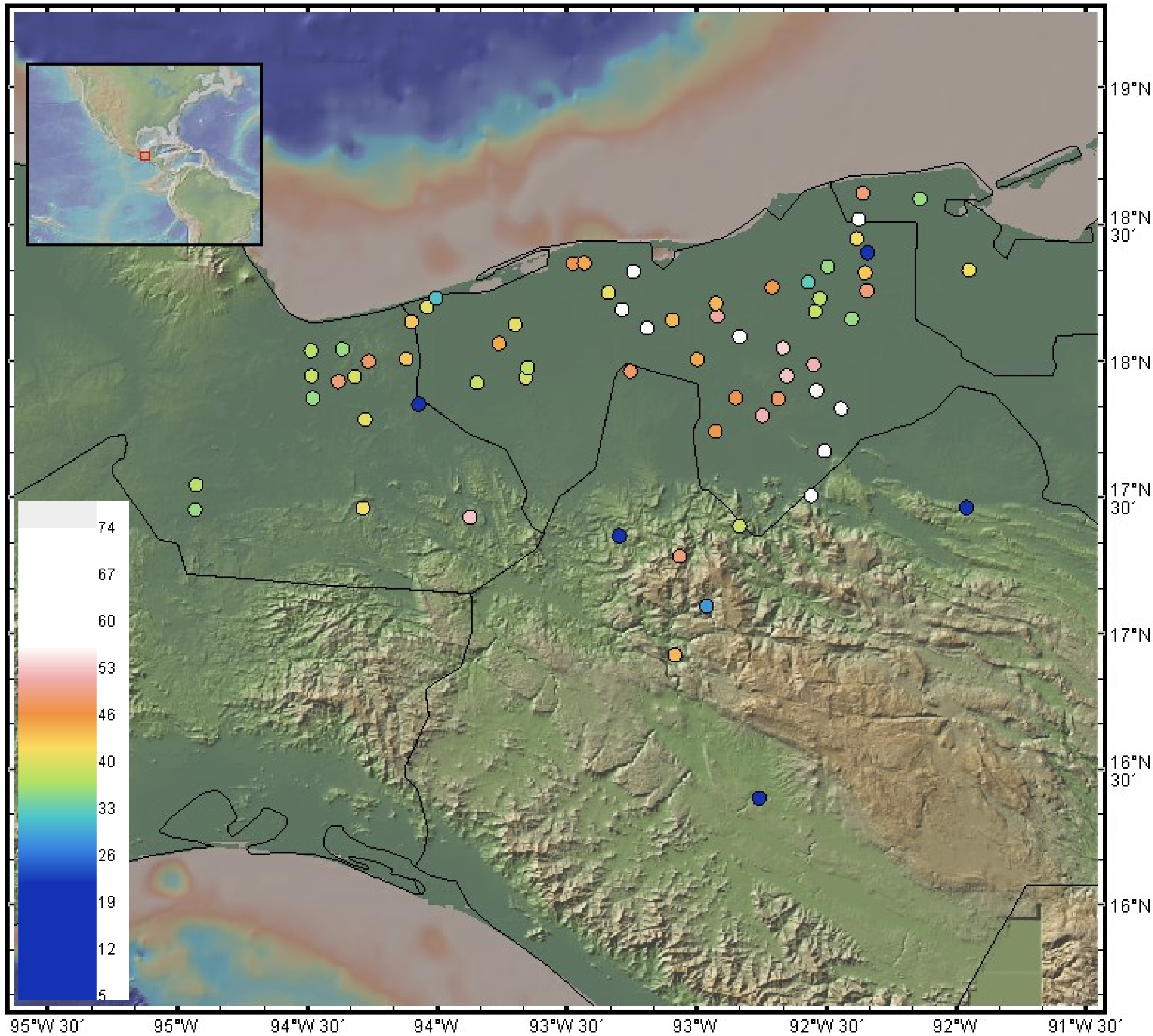

Figure 11: Southeast heat flow map of México.

4. SUMMARY OF FINDINGS AND CONCLUDING REMARKS

This work provides the first "preliminary" map of Mexico's geothermal resources, which is useful to locate low, medium, and high enthalpy heat reserves suitable for electricity production or utilization in direct uses.

The increased number and combination of heat flow measurements will improve the knowledge on heat flow contouring and information for several regions. This will leads to more accurate interpretations of the stored heat reserves in the crust. Nevertheless, these results and interpretations are still preliminary due to the scarcity of direct measurements in the continent.

Future work will include a definition of tectono-thermal provinces and their local anomalies as well as an analysis of the relationship between borehole measurements and indirect methods to estimate heat flow. 2D and 3D thermal models could be developed in the areas with high density of geological and thermal data. This work will increase the knowledge of heat flow in México, and will allow construction of an updated (and highly necessary) geothermal map of México.

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elevation site, geothermal gradient and thermal conductivity by special request of the data providers (CFE and PEMEX), because of the recent modifications to the energy regulations in México. The complementary data and thermal parameters were used exclusively for statistical and plot interpretations during this work.

REFERENCES

Arango-Galván, C., R. M. Prol-Ledesma, E. L. Flores-Márquez, C. Canet, and R. E. Villanueva (2011). Shallow submarine and subaerial, low-enthalpy hydrothermal manifestations in Punta Banda, Baja California, Mexico: Geophysical and geochemical characterization. *Geothermics*, **40**(2), 102-111. doi:10.1016/j.geothermics.2011.03.002.

Arango-Galván, C., R. M. Prol-Ledesma and M. A. Torres-Vera (2015). Geothermal prospects in the Baja California Peninsula. *Geothermics*, **55**, 39-57. doi: 10.1016/j.geothermics.2015.01.005.

Barragán, R. M., P. Birkle, E. Portugal, V. M. Arellano, and J. Alvarez (2001). Geochemical survey of medium temperature geothermal resources from Baja California and Sonora, Mexico. *Journal of Volcanology and Geothermal Research*, **110**, 101-119. doi:10.1016/S0377-0273(01)00205-0.

Beardsmore, G. R., and J. P. Cull (2001). *Crustal heat flow: A guide to measurement and modelling*. First ed. Cambridge University Press, Cambridge, United Kingdom. 324 pp. doi: 10.1017/CBO9780511606021.

Beltran-Abaunza, J. M., and A. L. Quintanilla-Montoya (2001). Calculated heat flow for the Ensenada region, Baja California, Mexico. *Ciencias Marinas*, **27**(4), 619-634.

Blackwell, D.D., and M. Richards (2004). Geothermal map of North America. *American Association of Petroleum Geologist* (AAPG), 1 sheet, scale 1:6,500,000.

Bonté, D., J.-D. van Wees, and J. M. Verweij (2012). Subsurface temperature of the onshore Netherlands: new temperature dataset and modelling. *Netherlands Journal of Geosciences*, **91**(4), 491-515. doi: http://dx.doi.org/10.1017/S0016774600000354.

Bullard, E. C. (1939). Heat flow in South Africa. *Proceedings of the Royal Society of London Series A, Mathematical and Physical Sciences*, **173**, 474-502. doi: 10.1098/rspa.1939.0159.

Chapman, D. S. (1986). Thermal gradient in the continental crust. *Geological Society, London, Special Publications*, **24**, 63-70. doi:10.1144/GSL.SP.1986.024.01.07.

Chapman, D. S., and L. Rybach (1985). Heat flow anomalies and their interpretation. *Journal of Geodynamics*, **4**(1-4), 3-37. doi:10.1016/0264-3707(85)90049-3.

Chávez, R. E., E. L. Flores, J. O. Campos, M. Ladrón de Guevara, M. C. Fernández-Puga, and J. Herrera (2000), Three-dimensional structure of the Laguna Salada Basin and its thermal regime, *Geophysical Prospecting*, **48**, 835-870. doi: 10.1046/j.1365-2478.2000.00215.x.

Clauser, C. and E. Huenges (1995). Thermal conductivity of rocks and minerals. In *Rock Physics & Phase Relations: A Handbook of Physical Constants*, edited by T. J. Ahrens, AGU Reference Shelf, Vol. 3, pp. 105-126, American Geophysical Union.

Deming, D. (1989). Application of bottom-hole temperature corrections in geothermal studies. *Geothermics*, **18**(5-6), 775-786. doi:10.1016/0375-6505(89)90106-5.

Elders, W.A., D.K. Bird, A.E. Williams and P. Schiffman (1984). Hydrothermal flow regime and magmatic heat source of the Cerro Prieto geothermal system, Baja California, Mexico. *Geothermics*, **13**, 27-47. doi:10.1016/0375-6505(84)90005-1.

Espinosa-Cardeña, J.M. and J.O. Campos-Enriquez (2008). Curie point depth from spectral analysis of aeromagnetic data from Cerro Prieto geothermal area, Baja California, México. *Journal of Volcanology and Geothermal Research*, **176**, 601–609. doi:10.1016/j.jvolgeores.2008.04.014.

Espinoza-Ojeda, O. M., E. Santoyo, and J. Andaverde (2011). A new look at the statistical assessment of approximate and rigorous methods for the estimation of stabilized formation temperatures in geothermal and petroleum wells. *Journal of Geophysics and Engineering*, **8**, 233-258. doi:10.1088/1742-2132/8/2/010.

Espinoza-Ojeda, O. M., R. M. Prol-Ledesma, E. R. Iglesias, and A. Figueroa-Soto (2017). Update and review of heat flow measurements in Mexico. *Energy*, **121**, 466-479. http://dx.doi.org/10.1016/j.energy.2017.01.045.

Flores-Márquez, E. L., R. Chávez-Segura, O. Campos-Enríquez, and M. Pilkington (1999). Preliminary 3-D structural model from the Chicxulub impact crater and its implications in the actual geothermal regime. *Trends in Heat, Mass & Momentum Transfer*, **5**, 19-40.

Gutiérrez-Negrín, L.C. (2015). Mexican Geothermal Plays. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

Gutiérrez-Negrín, L.C., R. Maya-González and J.L. Quijano-León. (2015). Present Situation and Perspectives of Geothermal in Mexico. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

Harrison, W.E., Luza, K.V., Prater, M.L., Chueng, P.K., Ruscetta, C.A. 1983. Geothermal resource assessment in Oklahoma. In: Geothermal Energy Exploration and Resource Assessment Technical Conference. Salt Lake City, 01 July.

Hasterok, D., and D. S. Chapman (2007). Continental thermal isostasy: 1. Methods and sensitivity. *Journal of Geophysical Research*, **112**(B06414), 1-15. doi:10.1029/2006JB004663.

Iglesias, E. R., R. J. Torres, I. Martínez-Estrella, and N. Reyes-Picasso (2011). Summary of the 2010 assessment on medium- to low-temperature geothermal resources in Mexico. *Geotermia, Revista Mexicana de Geoenergía*, **24**(2), 39-48.

Iglesias, E. R., R. J. Torres, I. Martínez-Estrella, and N. Reyes-Picasso (2015). Summary of the 2014 assessment on medium- to low-temperature Mexican geothermal resources. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

Jessop, A. M. (1990). *Thermal Geophysics*. Developments in Solid Earth Geophysics Series, Vol 17, Elsevier, 306 pp. doi: 10.1016/0040-1951(91)90030-V.

Kehle, R.O., Schoeppel, R.J., Deford, R.K., 1970. The AAPG geothermal survey of North America. In: Proceedings of the United Nations Symposium on the Development and Utilization of Geothermal Resources, vol. 2, pp. 358–367.

Kutasov, I. M. (1999). *Applied Geothermics for Petroleum Engineers*. First ed. Elsevier Scientific Publishing Company. 347 pp.

Kutasov, I. M., and L. V. Eppelbaum (2010). A new method for determining the formation temperature from bottom-hole temperature logs. *Journal of Petroleum and Gas Engineering*, **1**(1), 1-8.

Lee, T.-C., and T. L. Henyey (1975). Heat flow through the southern California borderland. *Journal of Geophysical Research*, **80**(26), 3733-3743. doi:10.1029/JB080i026p03733.

Liu C., K. Li, Y. Chen, L. Jia and D. Ma (2016). Static formation temperature prediction based on bottom hole temperature. *Energies*, **2016**, 9, 646. doi:10.3390/en9080646.

Lorenzo Pulido, C., M. Flores Armenta, and G. Ramírez Silva (2011). Characterization of a hot dry rock reservoir at Acoculco geothermal zone, Pue. *Geotermia, Revista Mexicana de Geoenergía*, **24**(1), 59-69.

Manea, M., and V. C. Manea (2011). Curie point depth estimates and correlation with subduction in Mexico. *Pure and Applied Geophysics*, **168**(8/9), 1489-1499. doi: 10.1007/s00024-010-0238-2.

Prol, R. M., and G. Juarez (1985). Silica geotemperature mapping and thermal regime in the mexican volcanic belt. *Geofisica Internacional*, **24**(4), 609-621.

Prol-Ledesma, R. M., and G. Juarez M. (1986). Geothermal map of Mexico. *Journal of Volcanology and Geothermal Research*, **28**(3-4), 351-362. doi: 10.1016/0377-0273(86)90030-2.

Prol-Ledesma, R.M. (1991). Chemical geothermometers applied to the study of thermalized aquifers in Guaymas, Sonora, Mexico: a case history. *Journal of Volcanology and Geothermal Research,* **46**, 49-59. doi: 10.1016/0377-0273(91)90075-B.

Reiter, M. and Tovar, J.C. (1982). Estimates of terrestrial heat flow in northern Chihuahua, Mexico, based upon petroleum bottom-hole temperatures. *Geological Society of America Bulletin,* **93**, 613-624. doi: 10.1130/0016-7606(1982)93<613:EOTHFI>2.0.CO;2.

Rosales-Rodríguez, J., W. L. Bandy, and E. Centeno-García (2014). Profundidad de la base de la fuente magnética y estructura térmica del Golfo de México. *Revista Mexicana de Ciencias Geológicas*, **31**(2), 190-202.

Sass, J. H., and G. Beardsmore (2011). Heat flow measurements, Continental In *Encyclopedia of Solid Earth Geophysics*, edited by H. K. Gupta, Springer. 569-573 pp.

Smith, D. L. (1974). Heat flow, radioactive heat generation, and theoretical tectonics for northwestern Mexico. *Earth and Planetary Science Letters,* **23**, 43-52. doi:10.1016/0012-821X(74)90028-4.

Smith, D. L., C. E. Nuckels III, R. L. Jones, and G. A. Cook (1979). Distribution of heat flow and radioactive heat generation in northern Mexico. *Journal of Geophysical Research*, **84**(B5), 2371-2379. doi: 10.1029/JB084iB05p02371.

Von Herzen, R.P. (1963). Geothermal heat flow in the Gulfs of California and Aden. *Science*, **140**, 1207-1208. doi:10.1126/science.140.3572.1207.

Von Herzen, R.P. (1964). Ocean-floor heat-flow measurements west of the United States and Baja California. *Marine Geology*, **1**, 225-239. doi:10.1016/0025-3227(64)90061-1.

Wilhelm, H., Y. Popov, H. Burkhardt, J. Šafanda, V. Čermák, P. Heidinger, D. Korobkov, R. Romushkevich, and S. Mayr (2005). Heterogeneity effects in thermal borehole measurements in the Chicxulub impact crater. *Journal of Geophysics and Engineering*, **2**, 357-363. doi: 10.1088/1742-2132/2/4/S09.

Zare-Reisabadi, M., M. R. Kamali, M. Mohammadnia, and F. Shabani (2015). Estimation of true formation temperature from well logs for basin modeling in Persian Gulf. *Journal of Petroleum Science and Engineering*, **125**, 13-22. http://dx.doi.org/10.1016/j.petrol.2014.11.009.

Ziagos, J. P., D. D. Blackwell, and F. Mooser (1985). Heat flow in southern Mexico and the thermal effects of subduction. *Journal of Geophysical Research,* **90**, 5410-5420. doi: 10.1029/JB090iB07p05410.