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Continental Conductive Surface Heat Flow in Mexico - the Analysis from Deep Boreholes

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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 study zones. This allows us to establish the subsurface areas with high heat storage.

In Mexico, in recent decades a strong demand for energy has arisen due to the increasing human necessities. This has increased the pollution rates. Therefore, governmental agencies in collaboration with academic institutions, have focused on improving the techniques of exploitation of renewable energy resources. One of them is geothermal energy, with five high enthalpy geothermal fields under exploitation for power generation. In addition, it is documented that there are many sites with low and medium enthalpy, through the study of thermal manifestations. From 2017 to present, two scientific works related to conductive surface heat flow have been published, where new estimation values together with published data were presented to define an updated geothermal gradient and heat flow map (Espinoza-Ojeda et al., 2017; Prol-Ledesma et al., 2018).

In this context, 1119 new geothermal gradient datapoints were compiled, from them, 1011 sites were used to estimate new heat flow values. Plus the 261 heat flow values from Espinoza-Ojeda et al (2017a, 2017b) and Prol-Ledesma et al (2018), and 491 values compiled and published previously in the mentioned works. The new geothermal gradient and heat flow data were calculated by using thermal logs [Borehole Transient Temperature (TBT) and Bottom-Hole Temperature (BHT)] from the drilling stage of geothermal and petroleum deep boreholes. This new database allows us to define areas with thermal anomalies and to classify sites of low, medium and high enthalpy with more density of heat flow and geothermal gradient values.

1. INTRODUCTION

A suitable estimation of the geothermal potential from Geothermal Systems depends on the reliable knowledge of several geological, geophysical and geochemical parameters that describe these systems, e.g. Avellán et al (2018), Almaguer et al (2019), Jácome-Paz et al (2019). A very important geophysical parameter is the heat flow, which can be used to estimate the heat stored in the subsurface which can be exploited to produce electrical power and/or geothermal direct uses.

The geographical position and the geological characteristics make Mexico a privileged country in relation to geothermal energy. Although it is known that Mexico has a great potential to produce geothermal energy due to five high enthalpy geothermal developments (Cerro Prieto, Los Azufres, Los Humeros, Tres Vírgenes and Domo de San Pedro). It is also known that in the country there are more than 2000 thermal manifestations containing low and medium enthalpy thermal resources (Iglesias et al 2015).

Despite the aforementioned, there is no source that indicates exact data of the true geothermal potential of Mexico. In this context, some works have been published with very reliable information about the potential geothermal potential of Mexico, through heat flow, geothermal gradient or subsurface temperature maps, e.g. Blackwell and Richards (2004), Iglesias et al (2016), Prol-Ledesma and Morán-Zenteno (2019). However, these kinds of sources must be updated constantly. In this context, from some Mexican research projects focused on estimating the geothermal reserves in Mexico, published studies define several heat flow measurements obtained from geothermal and petroleum exploration boreholes, e.g. Prol-Ledesma et al (2016, 2018), Espinoza-Ojeda et al (2017a, 2017b). These pioneering works, however, date between 30 and more than 40 years ago, e.g. Smith (1974), Smith et al (1979), Reiter and Tovar (1982) and Ziagos et al (1985).

Hence, this work has the main objective of presenting a geothermal gradient and updated heat flow maps. To accomplish this objective, it was necessary to compile thermal logs [Borehole Transient Temperature (TBT) and Bottom-Hole Temperature (BHT)] and rock formation stratigraphy from the drilling reports of geothermal and petroleum deep boreholes. 1119 sites were analyzed to calculate geothermal gradient data, from them, 1011 sites were used to estimate new heat flow values. In addition, the analysis included the 261 heat flow values from Espinoza-Ojeda et al (2017a, 2017b) and Prol-Ledesma et al (2018), and 491 values compiled and published previously in the mentioned works.

2. METHODOLOGY

Following the methodology proposed in the works of Espinoza-Ojeda et al (2017a) and Prol-Ledesma et al (2018), which consists of data collection and processing to calculate new heat flow values, the main tasks are described as follows:

2.1 Database

A new database from the TBT and BHT measurement logs of 1119 drilled boreholes was created (Figure 1). The database specifically consists of TBT and BHT data sets logged from 33 geothermal and 1086 petroleum boreholes, respectively (see Figure 2). Then, a stratigraphic profile database built according to the geological reports was created. In this case, only 126 stratigraphic profiles were available (see Figures 3 and 4). The data used in this work was provided by Comisión Federal de Electricidad (CFE) and Petróleos Mexicanos (PEMEX). Also, the 261 heat flow values from Espinoza-Ojeda et al (2017a, 2017b) and Prol-Ledesma et al (2018), and 491 values compiled and published previously were used in this work, e.g. Smith (1974), Smith et al (1979), Reiter and Tovar (1982), Ziagos et al (1985) and IHFC (2011).

The location of all new and compiled continental heat flow data is shown in the map of Figure 1. Examples from temperature profiles (T-z) are shown in Figure 2. The T-z profiles from MEX0123 and MEX0810 represent petroleum and geothermal boreholes, respectively. And the stratigraphic profiles from the MEX0123 and MEX0810, are shown in Figure 3 and 4, respectively.

Table 1 summarizes a general description of the available parameters from the compiled data to construct the updated heat flow database for Mexico. From Table 1, “Location” corresponds to the boreholes with coordinate data; “Geothermal gradient” (°C/km) corresponds to the estimated values from compiled T-z measurements or published data; “Thermal conductivity” (W/m K) corresponds to the estimated values from stratigraphic profiles or harmonic mean thermal conductivity published data; “Average thermal conductivity” corresponds to the average Crust value, in this work, 2.5 W/m K was used as suggested by Prol-Ledesma et al (2018); “Rejected” corresponds to the cases with predominantly convective thermal profiles.

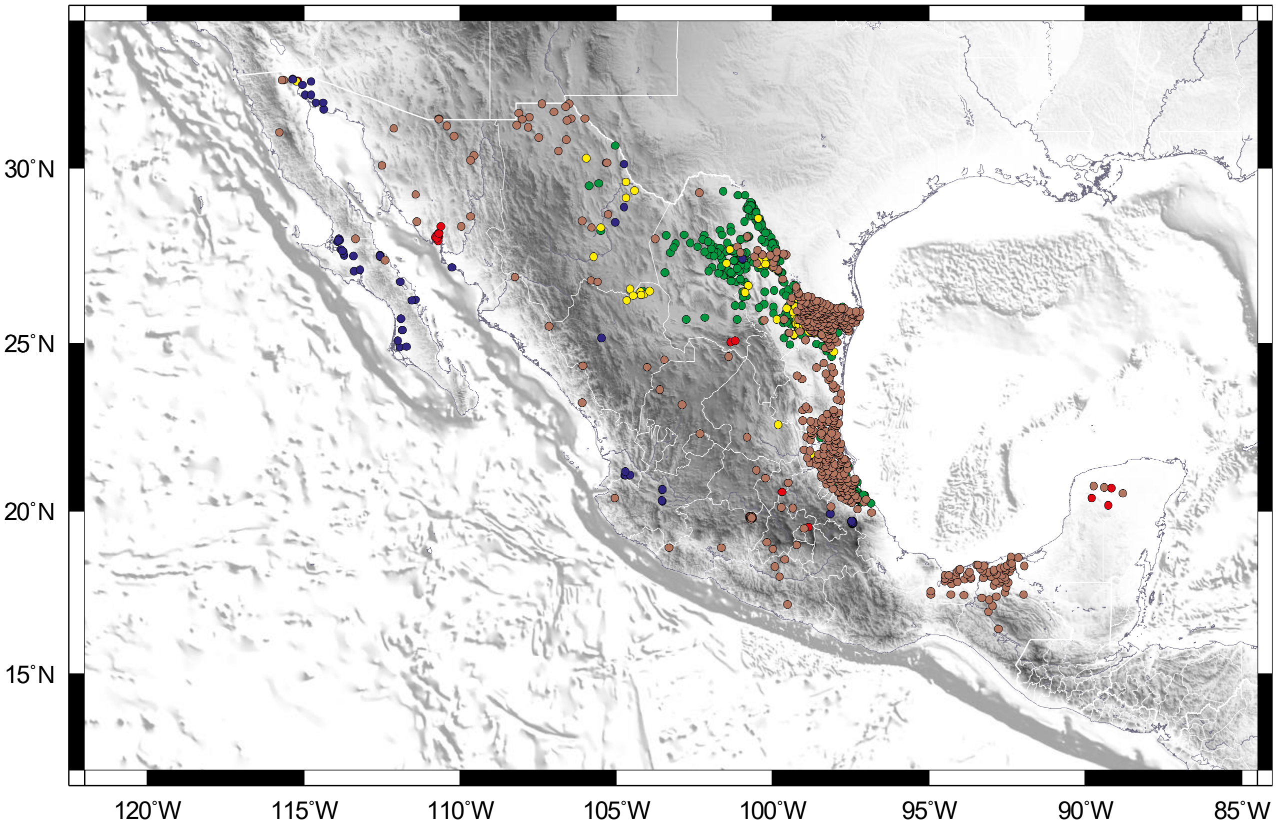

Figure 1: The updated continental heat flow data base of Mexico: Green (new heat flow sites); Blue (Espinoza-Ojeda et al, 2017a); Yellow (Espinoza-Ojeda et al, 2017b); Red (Prol-Ledesma et al, 2018); Brown (Smith, 1974; Smith et al, 1979; Reiter and Tovar, 1982; Ziagos et al, 1985; and IHFC, 2011).

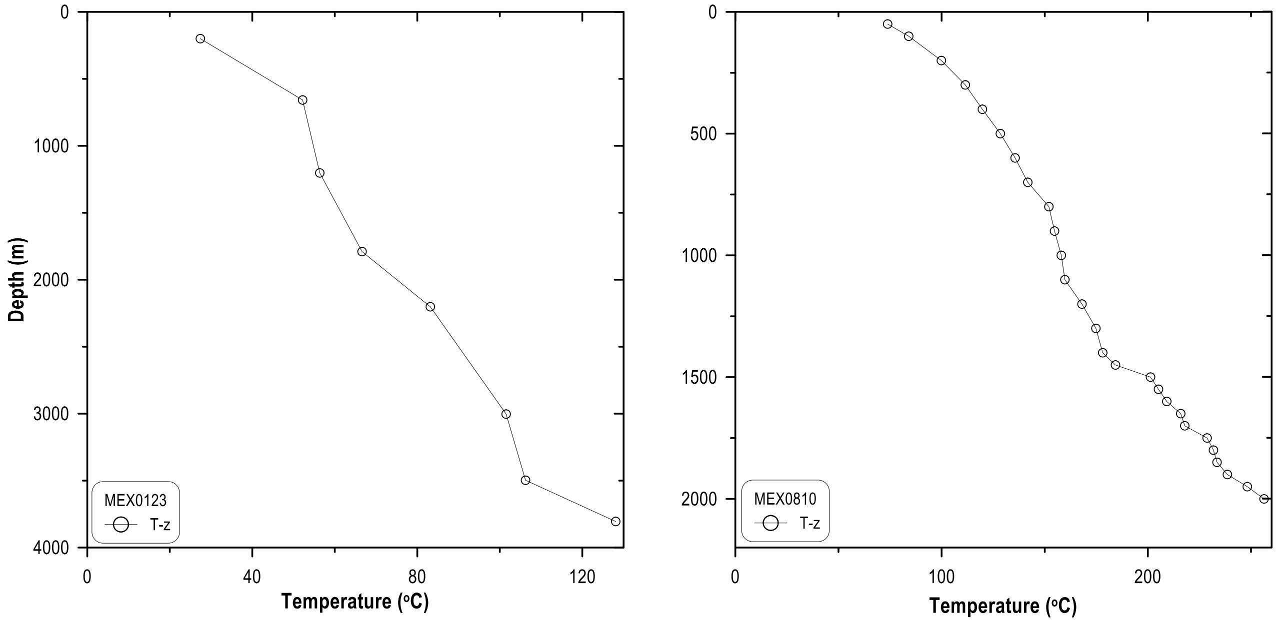

Figure 2: Plots of the Temperature-Depth profile (T-z) from the MEX0123 petroleum and MEX0810 geothermal borehole.

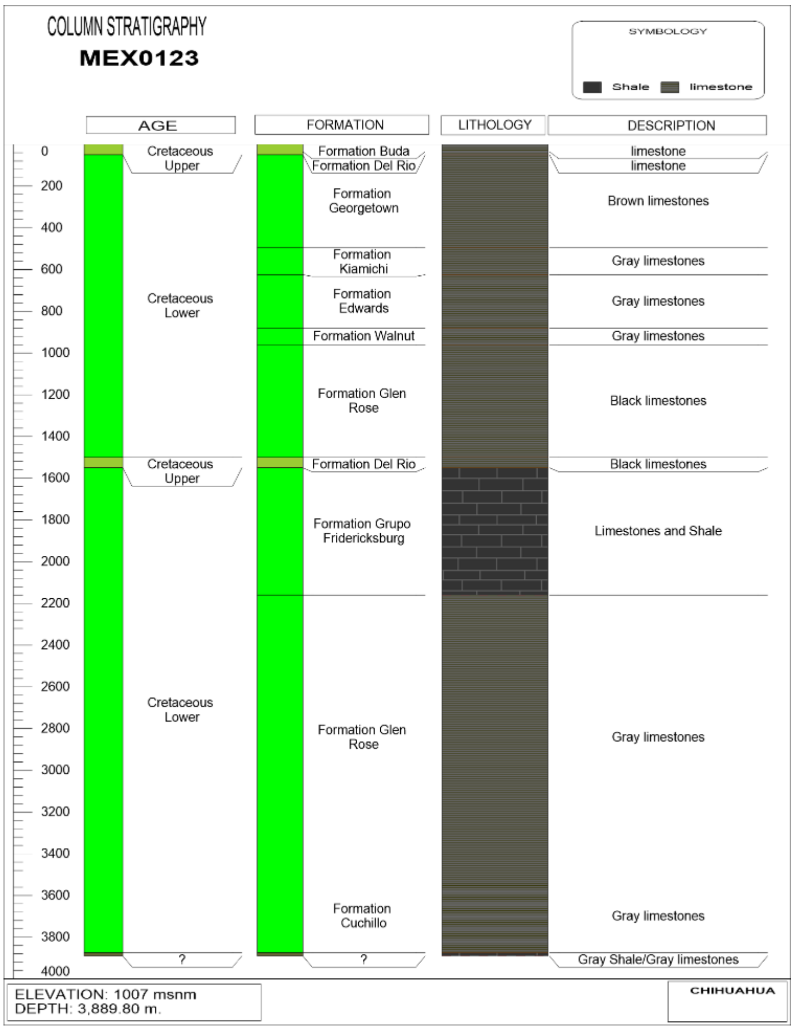

Figure 3: Description of the lithology from the petroleum borehole MEX0123.

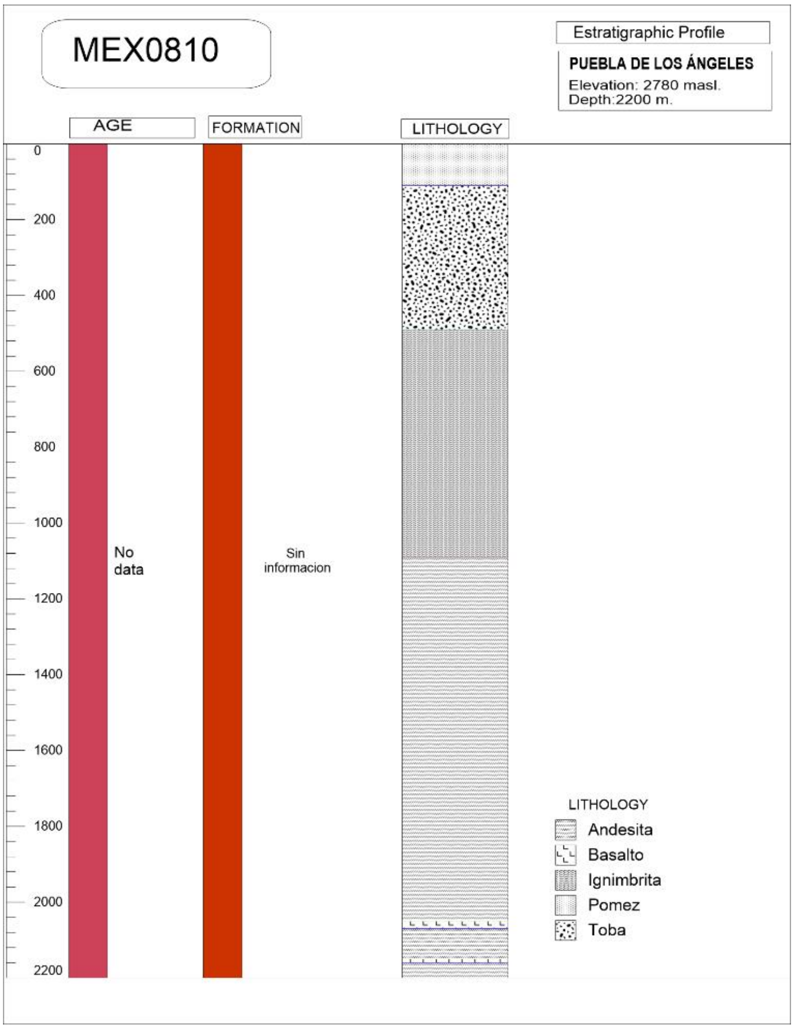

Figure 4: Description of the lithology from the geothermal borehole MEX0810. Andesita (Andesite), Basalto (Basalt), Ignimbrita (Ignimbrite), Pomez (Pumice), Toba (Tuff).

Table 2: Summary of the available parameters from the new and compiled data to update the Mexican heat flow database.

Parameter	No. of Boreholes
Location	1861
Geothermal gradient	1443
Thermal conductivity	346
Average thermal conductivity	1037
Rejected	108
Total	1871

2.2 Conductive heat flow

Heat flow is calculated using the Fourier's law equation that describes conductive heat transport phenomena:

$$q = -k(\mathrm{d}T/\mathrm{d}z) \qquad (1)$$

where q, k, T and z are heat flow, thermal conductivity, temperature and depth, respectively. For the purely conductive heat transfer between different materials (idealized case), to estimate heat flow in the presence of thermal conductivity variations, the Bullard method (Bullard, 1939) can be used:

$$T(z_i) = T_0 + q_0 R_i \quad (2)$$

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 (slope), and R_i is thermal resistance that can be expressed as:

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

where $k(z_i)$ is the thermal conductivity over the *i*th depth interval, Δz_i, and the summation is performed over *n* depth intervals from the surface to the depth of interest *z*. A simple extrapolation of the straight line from the apparent linear relationship between $T(z_i)$ measurements and the summed thermal resistance R_i allows the slope (q_0) and intercept (T_0) values to be determined. If the linear relationship is valid, a plot between $T(z_i)$ and R_i should exhibit a random scatter pattern with a narrow horizontal band, e.g. Miller and Miller (2000). Values that fall outside the narrow band are defined as outliers or rejected data, which are indicative to remove local convective effects, especially for those thermal measurements located within hydrothermal systems. In addition, as a test of linearity, the analysis of the coefficient of determination (R^2) to evaluate the actual relationships between $T(z_i)$ and R_i was performed. From the statistical point of view, R^2 expresses the amount of variation between $T(z_i)$ and R_i to determine if a linear relationship is the most suitable regression model to fit these parameters (i.e. when R^2 approaches 1), e.g. Miller and Miller (2000), Bevington and Robinson (2003). Therefore, if linearity deviation is presented, the borehole is disturbed by a convection flow, then, a low R^2 is calculated. Hence, undisturbed boreholes with an R^2 above 90% of confidence were considered for the construction of the heat flow database. Thermal data disturbed by convective heat transfer are easy to identify in high resolution temperature logs using a Temperature-Depth plot. Finally, disturbed boreholes with a R^2 below 90% of confidence were discarded.

All borehole data used in this study to calculate heat flow by the Bullard method satisfy some parameters of reliability: (1) must have at least three temperature-depth measurements and exceed 100 m in depth; (2) multiple gradient intervals are assigned to thermal conductivity values using a weighted average.

As an example, Figure 5 shows three different cases of petroleum boreholes. Figure 5a shows temperature increases semi-linearly with depth for borehole MEX0123; this semi-linear relationship apparently is preserved in the dependence between the temperature and thermal resistance in the Bullard plot with the exception of the second and the second to last data (Figure 5b). In the second case, borehole MEX0161 (Figure 5c and 5d), the linear relationship between *T-z* looks to be interrupted in the 1000-2000 m interval, even then, the linear tendency of the *T-z* and T_i-R_i plots predominate in the R2 analysis, where just one datapoint was rejected. In the third case, the borehole MEX0177 (Figure 5e and 5f), could be considered as the ideal example of conductive heat transfer process, according to the *T-z* plot and the R^2 result from the Bullard plot.

On the other hand, Figure 6 involves three geothermal boreholes as illustrative examples. Figure 6a and 6b represent the *T-z* and the Bullard plot from the borehole MEX0121, respectively. This case could be considered as pure conductive heat flow, since the linearity between *T-z* and T_i-R_i plots is undisturbed, R^2 value supports this statement. In the case of the borehole MEX0810, Figure 6c and 6d, a semi-linearity in the *T-z* and T_i-R_i plots is evident. The calculated R^2 and most data fall inside the 90% confidence limits, this validates the predominant linearity in the borehole MEX0810. And finally, the borehole MEX0819, as a representative example of perturbed borehole by dominant convective heat transfer in the subsurface. This case is one of the 108 boreholes rejected from the conductive surface heat flow database.

3. RESULTS

Once published heat flow data were compiled, and the newly obtained 1119 sites were analyzed to estimate 1011 new heat flow values, the Mexican heat flow database was updated. Therefore, the database is integrated by 1754 continental heat flow measurements.

Figure 7 and 8 show the histogram from the available geothermal gradient estimations, the published and new heat flow values, respectively. Due to lack of space and the numerous data used in this work, we decided to group the data in two energy flux subsets to aid visualization of the distribution of the data. From both Figures (7 and 8), it is evident that the updated database, geothermal gradient, and heat flow values are of non-uniform distribution. From Figure 7a, the most numerous geothermal gradient estimations are located in the interval 20-50 °C/km, that probably is related to the interval 30-120 mW/m^2 (Figure 8a) due to the direct proportionality with heat flow. The histograms illustrated in Figure 7a and 8a, once again, demonstrate that Mexico has very large numbers of sites considered as low and medium enthalpy. The high and very high geothermal gradient (Figure 7b) and heat flow estimations (Figure 8b), considered as high enthalpy sites, are located in geothermal zones as it has been already shown in the works of Espinoza-Ojeda et al (2017a) and Prol-Ledesma et al (2018). In spite of the updated heat flow database with the integration of a large number of new values, the site distribution of heat flow values is still non uniform in the Mexican territory.

Figure 9, as an illustrative example, contains a map with the location of the heat flow data that correspond to the energy subset of 0-120 mW/m^2, where most of the numerical values are between 30 and 120 mW/m^2 as shown in Figure 8a. From the 1609 heat flow sites shown in Figure 9, we can surmise that the distribution of the zones considered as having low and medium (<70 mW/m^2) enthalpy are located mainly in southern Mexico. Zones with energy levels from medium to high enthalpy are predominately concentrated in the northern areas and eastern Mexico.

This work provides additional data to locate low, medium, and high enthalpy heat reserves. Besides, the currently compiled and new estimated thermal data provide a suitable and improved regional inventory map of unknown low and medium enthalpy sites. In addition, the constant task of updating and improving the heat flow and geothermal gradients database of Mexico was achieved in this work. This has a direct impact in the geothermal industry and even in the petroleum industry, considering that most of the evaluated sites are petroleum boreholes.

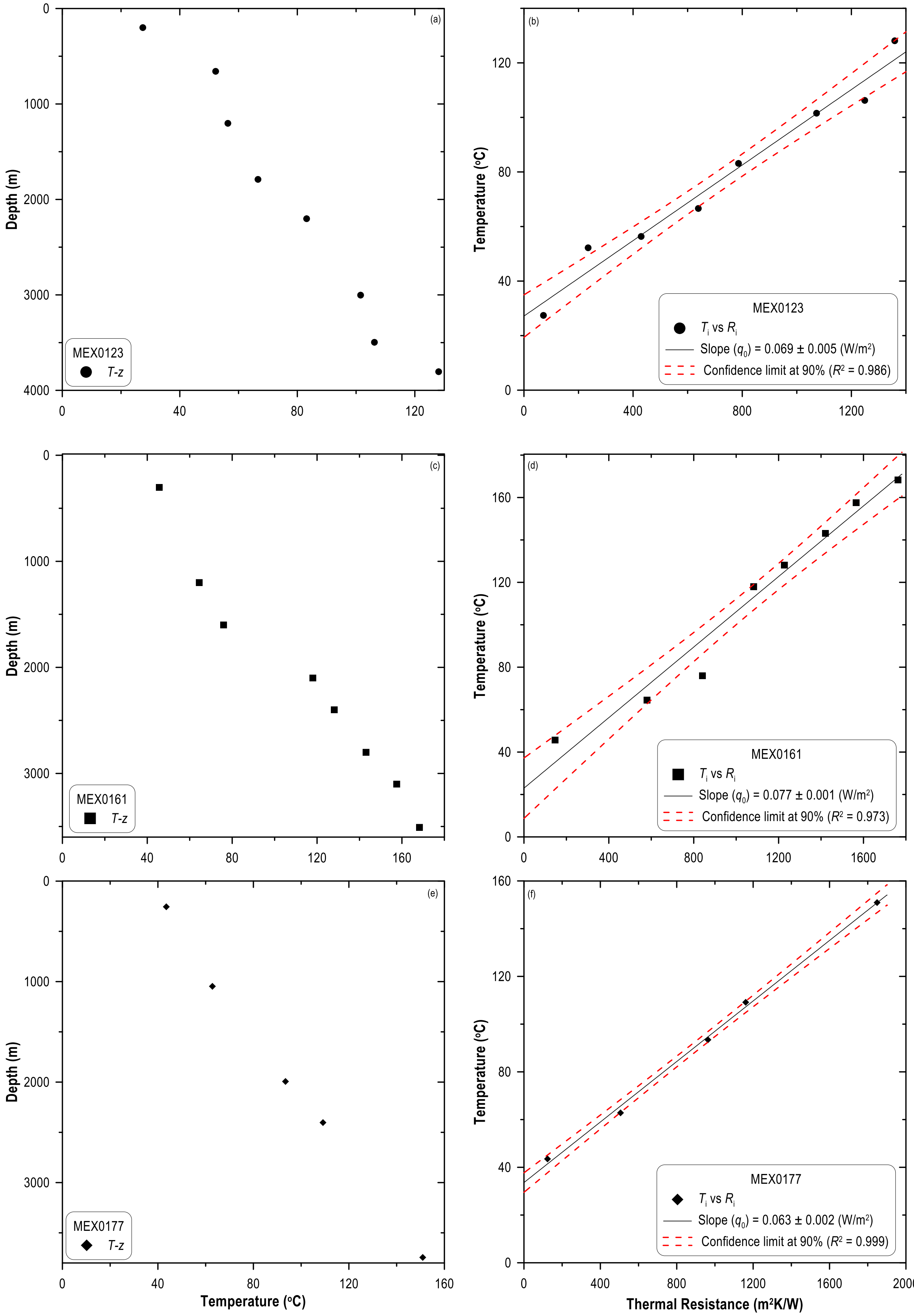

Figure 5: (a) Temperature-Depth profile and (b) Bullard plot from borehole MEX0123; (c) Temperature-Depth profile and (d) Bullard plot from borehole MEX0161; (e) Temperature-Depth profile and (f) Bullard plot from borehole MEX0177.

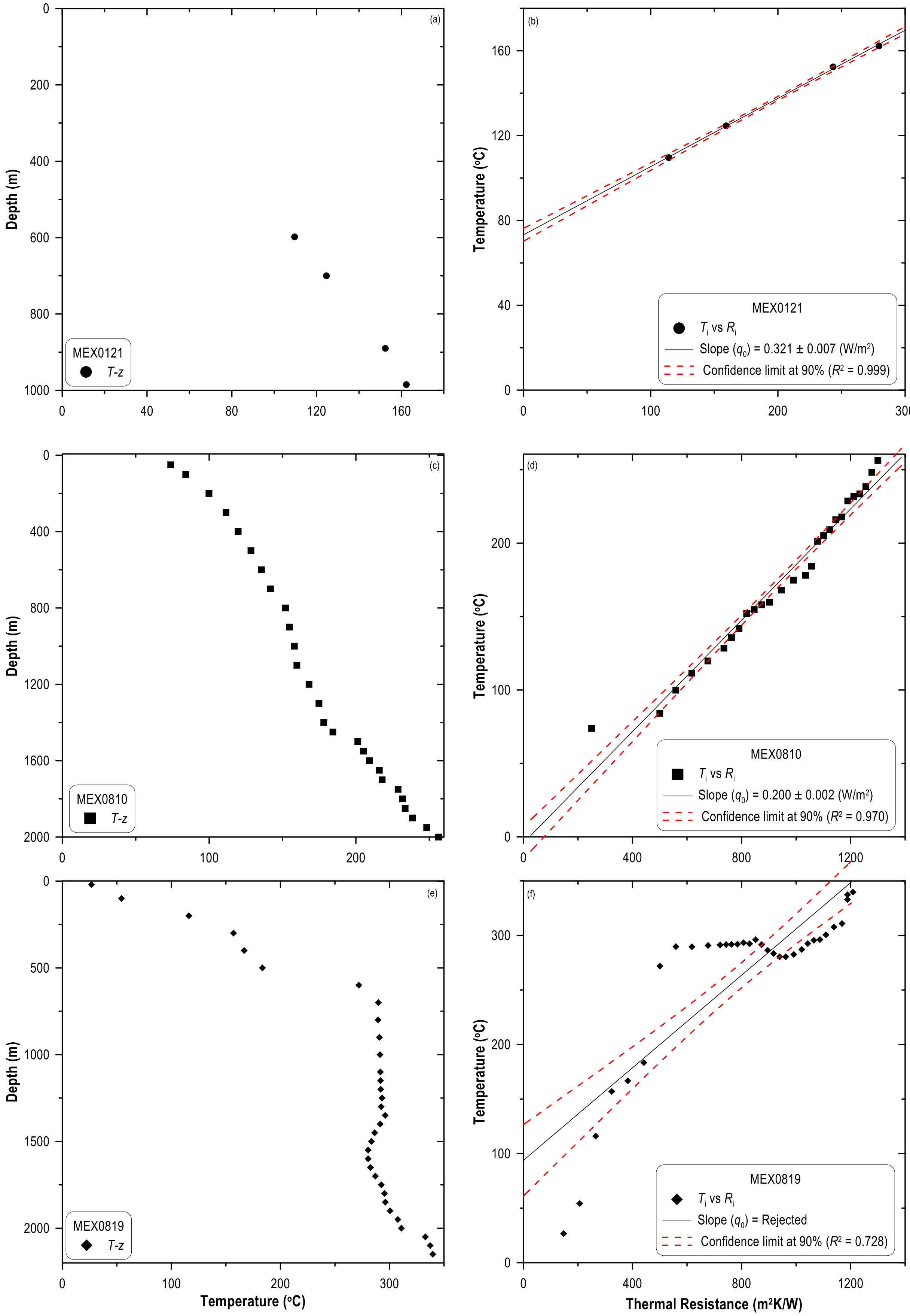

Figure 6: (a) Temperature-Depth profile and (b) Bullard plot from borehole MEX0123; (c) Temperature-Depth profile and (d) Bullard plot from borehole MEX0161; (e) Temperature-Depth profile and (f) Bullard plot from borehole MEX0177.

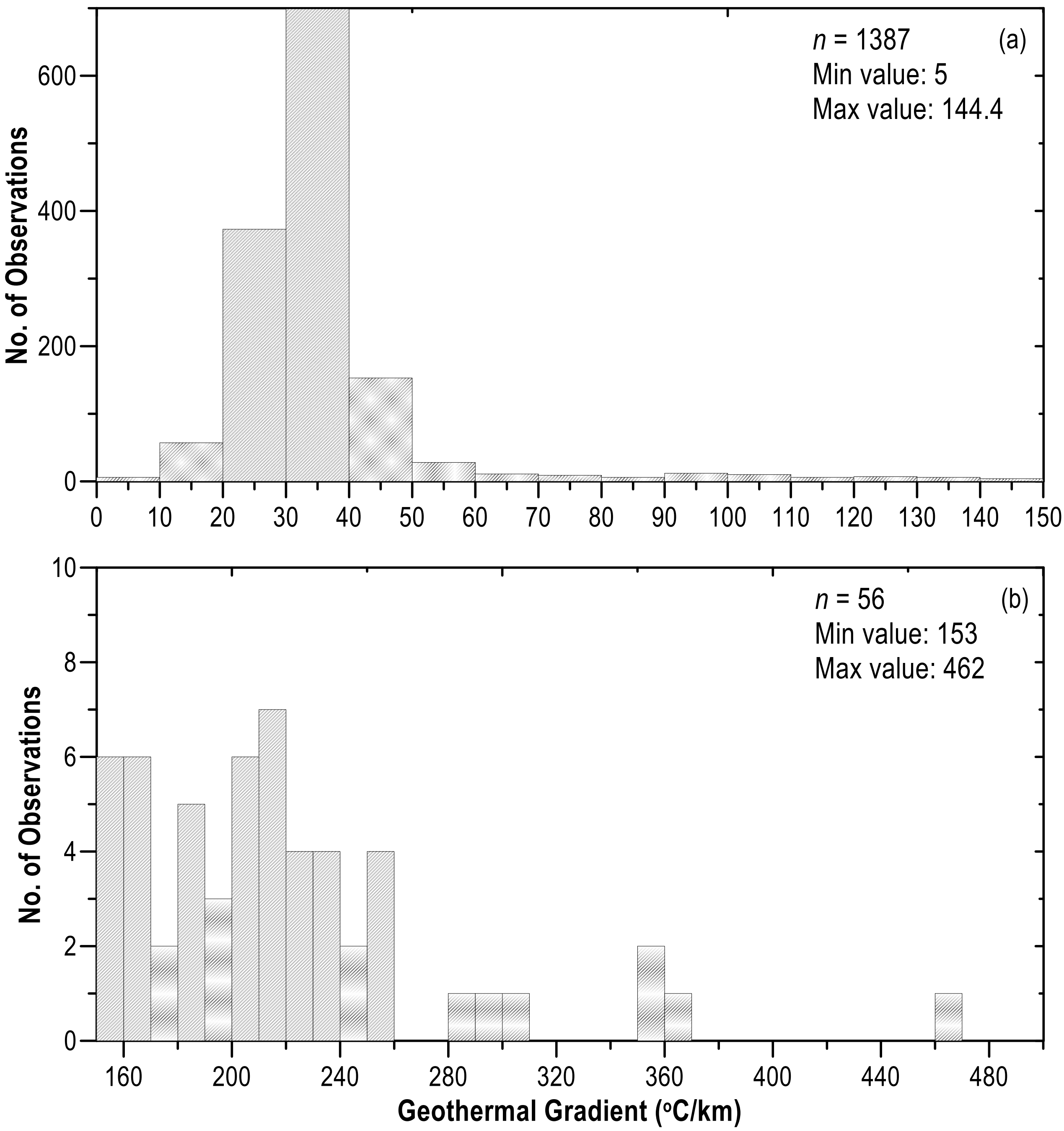

Figure 7: Histogram plots of the compiled continental geothermal gradients estimations from Mexico: (a) values from 0-150 °C/km; and (b) values from 150 to 500 °C/km.

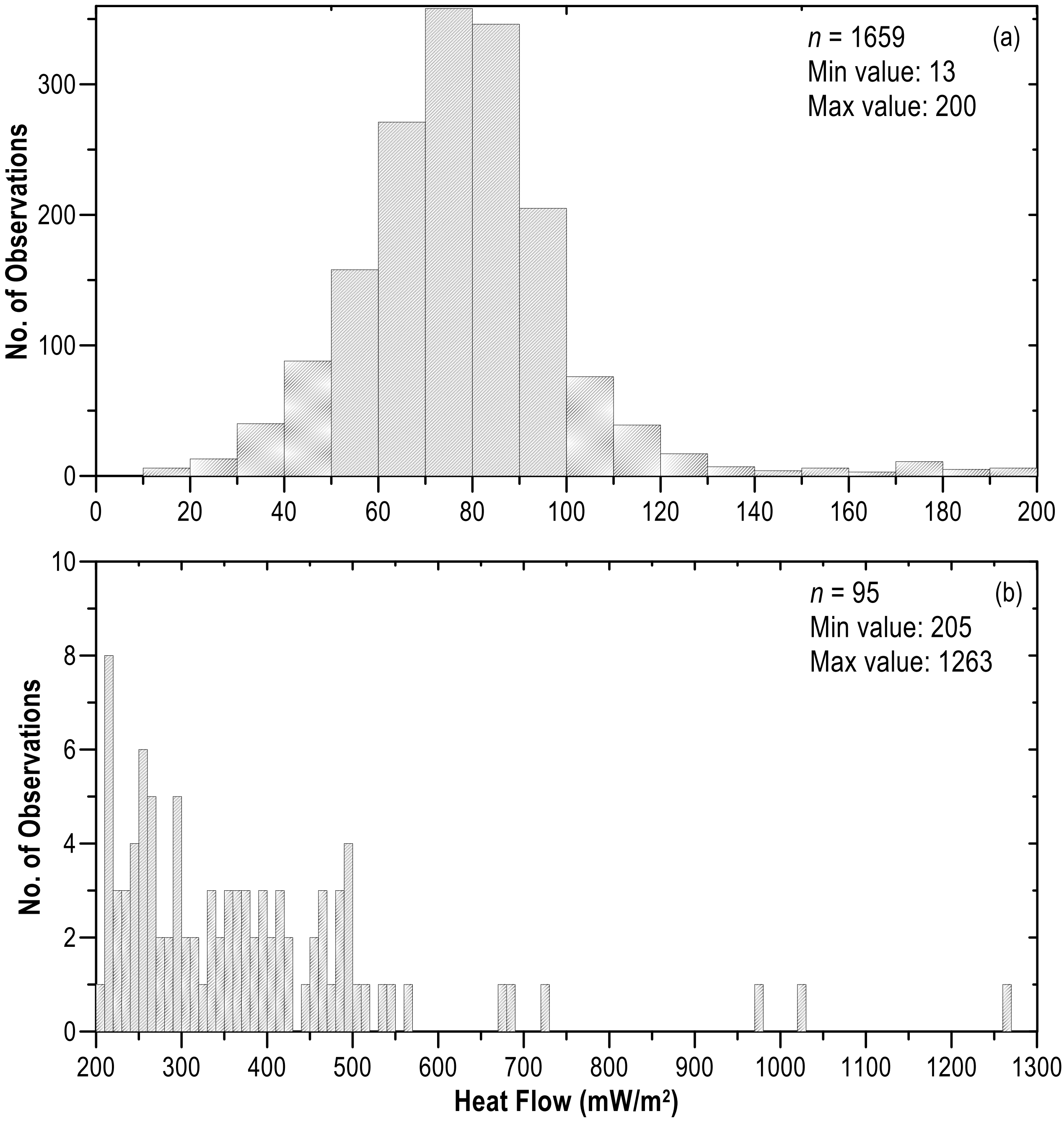

Figure 8: Histogram plots of the overall continental heat flow measurements from Mexico: (a) compiled heat flow values from 0-200 mW/m^2; and (b) compiled heat flow values from 200 to 1300 mW/m^2.

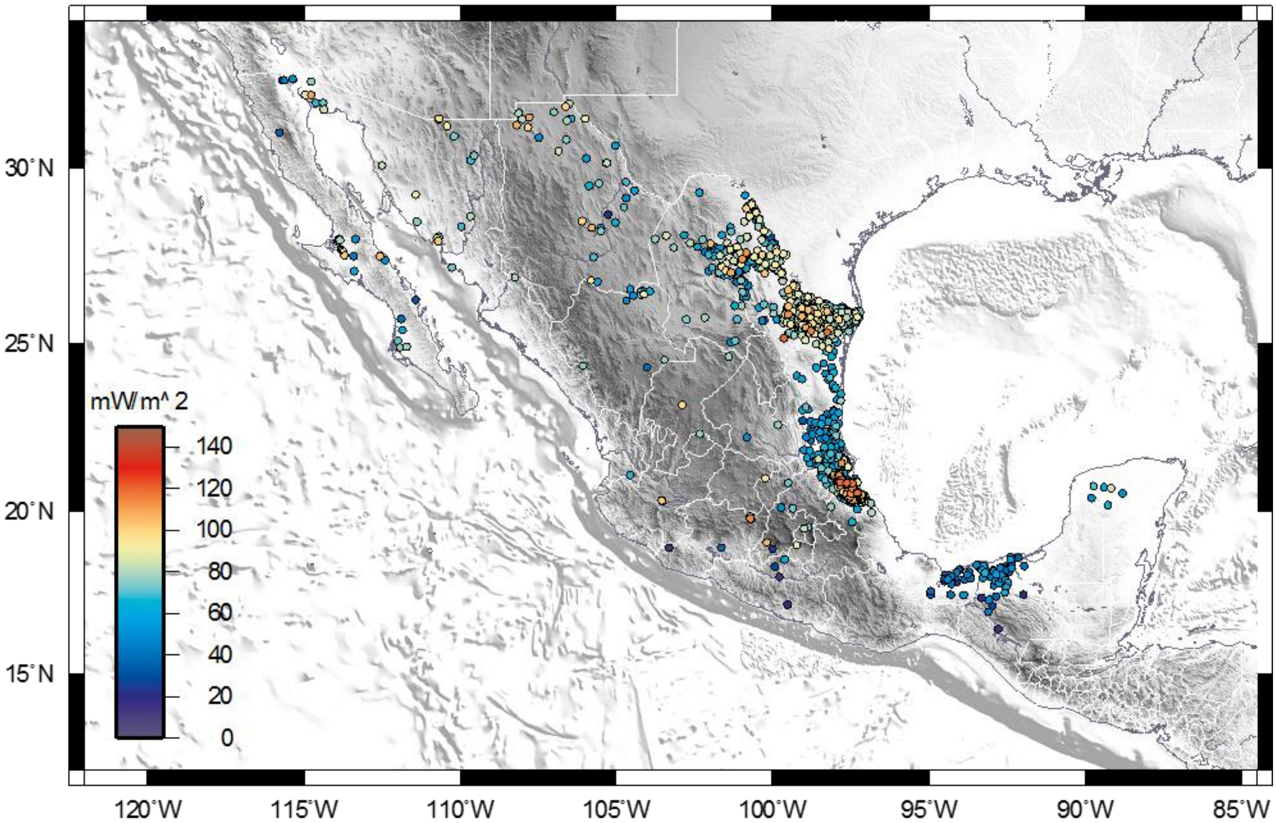

Figure 9: Continental heat flow map of Mexico (Update 2019). Location and distribution of the heat flow sites considered in the interval 0-120 mW/m^2.

4. CONCLUSIONS

This work represents, the fourth compilation of published and new heat flow data in Mexico. The increased number and combination of heat flow measurements will aid to improve the proposed heat flow contouring maps by Prol-Ledesma et al (2018) and Prol-Ledesma and Morán-Zenteno (2019).

The updated heat flow database will be indispensable for the accurate interpretations of the stored heat reserves in the crust. The heat flow anomalies reported in this work lead to the location of promising areas for exploitation and direct use of geothermal energy.

As future work, the constant updating of heat flow measurements is necessary to reveal low, medium, and high enthalpy resources in large areas that remain uncharted.

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