Relationship between Heat Flow and Depth to the Bottom of the Magnetic Source in Mexico

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ABSTRACT

The Depth to the Bottom of Magnetic Source (DBMS) is widely associated with the Curie Temperature isotherm and used to characterize the thermal structure of the Earth. The study of the relationships between the DBMS and Heat Flow is important because high Heat Flow anomalies can be related, assuming a conductive and steady-state thermal regime, with shallower DBMS zones. This study characterizes the relationship between Heat Flow and DBMS throughout Mexico using a Generalized Linear Model with DBMS data calculated using the spectral analysis method from aeromagnetic data employing 64x64 km windows distributed throughout the country. Heat Flow data, clustered in economically relevant and research areas, were compiled from published papers and calculated using temperature logs from wells, by applying the Bullard plot method. In terrains with complex geology like Mexico, the DBMS can be associated with different physical features that are not necessarily the Curie isotherm, as for instance a lithological boundary.

1. INTRODUCTION

In crustal thermal studies is common the use of temperature estimators at depth due to lack of data, complexity and elevated drilling costs derived from obtaining temperature logs and surface heat flow data on wells. A widely used solution to this problem is using the DBMS calculated from the spectral analysis and inversion of aeromagnetic data. DBMS is associated with the Curie Temperature Depth (CTD) and used to estimate the geothermal gradient and surface heat flow (Okubo et al., 1985; Haggerty, 1978; Gasparini et al., 1979; Conrad et al., 1983; Blakely, 1988; Campos-Enriquez et al., 1980; Wasilewski and Mayhew, 1992; Tsokas et al., 1998; Tanaka et al., 1999; Ross et al., 2006; Espinosa-Cardeña and Campos-Enriquez, 2008; Bouligan et al., 2009; Li et al., 2010; Manea and Manea, 2011; Hsieg et al., 2014; Rosales et al., 2014; Gao et al., 2015; Li et al., 2017; Martos et al., 2017; Martos et al., 2018). The estimation of temperature and heat flow using the DCT is a reconnaissance regional method (Tanaka et al., 1999) and some thermal mappings that were carried out using this technique do not yield the expected results. For this reason, the aim of this work is analyzing the relationship between heat flow data measured in wells and calculated DBMS.

Diverse physical characteristics are associated with the DBMS when the correlation coefficient with Heat Flow is low, for example, lithological boundaries associated with volcanic rocks overlying non-magnetic rocks as limestones, also, changes on the lithology and mineralogy of the magnetic basement is reflected in different values for the Curie temperature affecting the studied relationship. Another consideration is the inconsistencies in the processing the data, as is the use of arbitrary filters that affect the lowest wave-numbers (Gasprini et al., 1979; Blakely, 1988; Ravat et al., 2007; Rosales-Rodríguez et al., 2014).

The use of statistical tools and geographic information systems in data analysis is essential to reach consistent results.

2. DATA AND METHODS

For this study the aeromagnetic data used was the collected by the Consejo de Recursos Minerales, now Servicio Geológico Mexicano (SGM), from aeromagnetic surveys since 1962, while the surface heat flow was calculated from temperature and thermal conductivity obtained in wells consulted in technical reports or papers, published by Prol-Ledesma et al. (2018).

2.1 Heat flow calculation using well data

The calculation of surface heat flow supposes conductive and isotropic heat transfer mechanism without heat generation, studied by the Fourier´s Law in Eq. [1].

$$q = -k\left(\frac{dT}{dz}\right) \qquad [1]$$

Where q is surface heat flow, k is thermal conductivity, T is temperature and z are depth. We considered two types of data: Bottom-Hole Temperature (BHT) logs and continuous temperature logs. The Fourier´s Law was used in BHT logs and the Bullard method in the continuous temperature logs. Bullard method consists of to analyze the linear regression between the resistances and temperature in depth showed in Eq. [2].

$$T_d = T_O + q_O R \qquad [2]$$

Where T_d us temperature at depth, the intercept T_O is the temperature at the surface, the slope q_O is the surface heat flow and R is the thermal resistance expressed on Eq. [3].

$$R = \sum_i \left(\frac{\Delta z_i}{k_i}\right) \qquad [3]$$

Where k_i is the thermal conductivity in the i-th interval of depth and Δz_i is the thickness of the i-th interval. An example of the calculation is showed in Fig. 1.

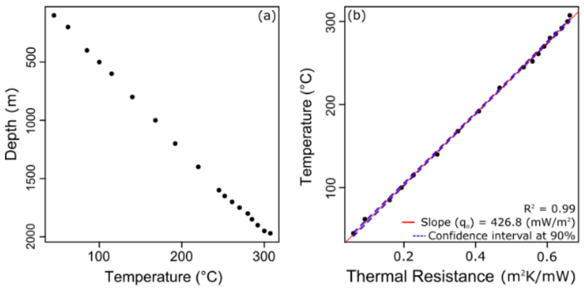

Figure 1: Temperature-depth profile (a) and Bullard plot (b) as an example of heat flow calculation. From Prol-Ledesma et al. (2018).

2.2 Magnetic data and Estimation of the Depth of Bottom of Magnetic Source

The magnetic data acquired from 1962 to 1992 were digitalized by hand from the intersections of the flight lines with magnetic contour lines resulting in 360,000 line-km digital data with the Definitive Geomagnetic Reference Field (DGRF) subtracted, grid constructed using a minimum curvature algorithm with a cell size one-fifth that of the flight-line spacing and filtered by the first vertical derivative in poorly merged areas. Since 1994 the acquisition was carried out using Cesium magnetometers positioned by differential GPS along north-south-trending flight lines spaced 1,000 m, flight height from 300 to 400 m above the terrain and data corrections by diurnal variations of the magnetic field, lag heading, DGRF/IGRF and tie-line mis-ties (North America Magnetic Anomaly Group, 2002).

From the aeromagnetic data the DBMS calculation was carried out using the centroid spectral method developed by Tanaka et al. (1999) as a modification of the Spector and Grant (1970) method.

Tanaka et al. (1999) calculated the top bound (Z_t) and the centroid (Z_0) of the magnetic source from the power spectrum of magnetic anomalies to estimate the DBMS (Z_b). Assuming a layer that extends infinitely in all horizontal directions as a random function of magnetization $M(x, y)$, the power density spectra of the total field anomaly $\Phi_{\Delta T}$, introduced by Blakely (1995), is Eq. [4].

$$\Phi_{\Delta T}(k_x, k_y) = \Phi_M(k_x, k_y) \times F(k_x, k_y) \qquad [4]$$

Where $F(k_x, k_y)$ is described in Eq. [5].

$$F(k_x, k_y) = 4\pi^2 C_m^2 |\Theta_m|^2 |\Theta_f|^2 e^{-2|k|Z_t}\left(1 - e^{-|k|(Z_b - Z_t)}\right)^2 \qquad [5]$$

From Eq. [4] and Eq. [5], Φ_M is power-density spectra of the magnetization, C_m is a proportionally constant, $|k|$ is the wavenumber, Θ_m is the magnetization direction and Θ_f is the geomagnetic field direction. The radial average of $\Phi_{\Delta T}$, if the Φ_M is constant because $M(x, y)$ is completely random and uncorrelated, is presented on Eq. [6].

$$\Phi_{\Delta T}(|k|) = Ae^{-2|k|Z_t}\left(1 - e^{-|k|(Z_b - Z_t)}\right)^2 \qquad [6]$$

A is a constant. The Eq. [6] becomes Eq. [7] when the wavelengths are less than about twice the thickness.

$$\ln\left(\Phi_{\Delta T}(|k|)^{\frac{1}{2}}\right) = \ln B - |k|Z_t \qquad [7]$$

B is a constant. The Eq. [7] is like a straight-line equation, where the slope estimates, at high wavenumbers, the top bound of the magnetic source (Figure 2a).

Rewriting the Eq. [6] as Eq. [8].

$$\Phi_{\Delta T}(|k|)^{\frac{1}{2}} = Ce^{-|k|Z_0}\left(e^{-|k|(Z_t - Z_0)} - e^{-|k|(Z_b - Z_0)}\right) \qquad [8]$$

C is constants. The approximation of the Eq. [8], at long wavelengths, is Eq. [9].

$$\Phi_{\Delta T}(|k|)^{\frac{1}{2}} = Ce^{-|k|Z_0}\left(e^{-|k|(-d)} - e^{-|k|(d)}\right) \sim Ce^{-|k|Z_0} 2|k|d \qquad [9]$$

Eq. [9] can be expressed as Eq. [10].

$$\ln\left(\left[\Phi_{\Delta T}(|k|)^{\frac{1}{2}}\right] / |k|\right) = \ln D - |k|Z_0 \qquad [10]$$

D is a constant. From the Eq. [10] is possible to estimate the centroid of the magnetic source calculating the slope of the straight-line at low-wavenumber (Figure 2b).

Finally, the DBMS is calculated using Eq. [11].

$$Z_b = 2Z_0 - Z_t \qquad [11]$$

The value estimated of DBMS is an average value of the entire window of analysis, the methodology could not delineate local shallow or deep thermal anomalies and the methodology is sensitive to finite data length (Tanaka et al., 1999).

DBMS was calculated for all the continental portion of Mexico and the Gulf of California, using a window size of 64 x 64 km overlapped 50% between every window using the *MAGMAP FILTERING* module of *Oasis Montaj*.

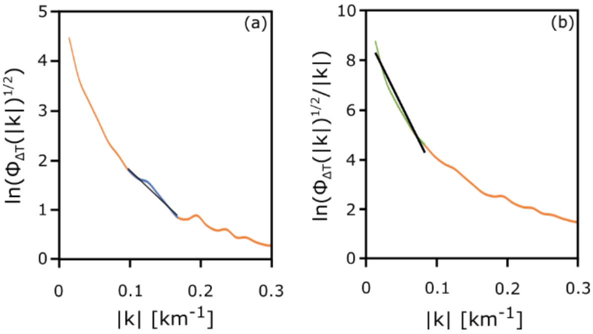

Figure 2: Example of (a) estimation of the top and (b) centroid of the magnetic source, using the spectral analysis.

2.3 distribution of data and statistical analysis

All the estimations of DBMS are in the continental portion of Mexico and the Gulf of California, meanwhile, the heat flow data are clustered mainly in economic zones as petroleum basins or geothermal plant generation (Fig. 3). To evaluate the heat flow with the DBMS, it was necessary to calculate the average value of surface heat flow of every analysis window using a geographic information system.

Finally, the statistical analysis was carried out using R version 3.4.0 evaluating all the univariate statistics and bivariate statistics, trying to find high correlation coefficients, similar as found by Hsieg et al. (2014) and Gao et al. (2015) with Pearson´s correlation coefficients of 0.62 and 0.65 respectively, because with high correlation coefficients it is possible to apply geostatistical techniques on heat flow maps, estimating the heat flow from DBMS.

In the univariate statistics, the DBMS result in a positive asymmetric and leptokurtic distribution (Fig. 4a, Table 1). Meanwhile, the heat flow data presents high positive asymmetry and leptokurtic distribution (Table 1, Fig. 4b), for this reason, it was necessary to apply the logarithmic transformation of the heat flow data to have better distribution (Table 1, Fig. 4C). The results of our analysis were carried out using bivariate statistics.

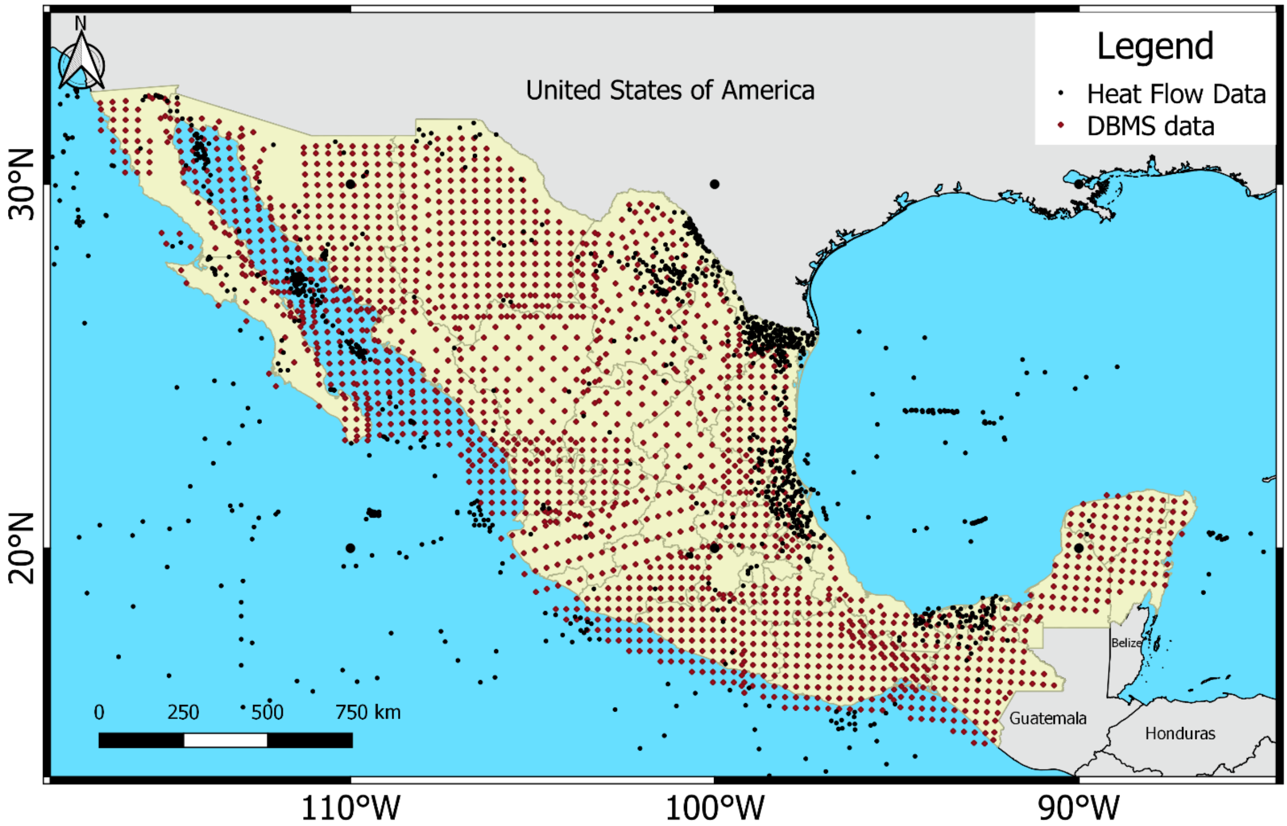

Figure 3: Distribution of Heat Flow and DBMS data.

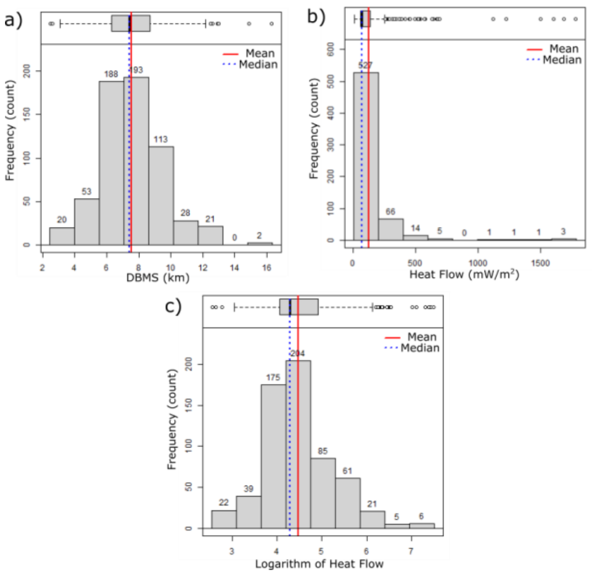

Figure 4: Histograms showing the distribution of the a) DBMS, b) Heat Flow and c) Logarithm of Heat Flow.

3. RESULTS

From 618 windows, with average heat flow and DBMS, analyzed, the correlation coefficients calculated (Table 2) are below 0.30 (less than the 30%), for this the scatterplot showed dispersion of the data (Fig. 5).

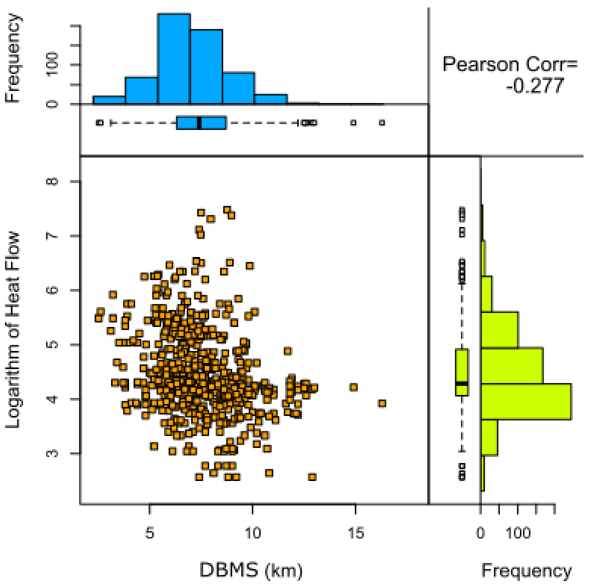

Figure 5: Scatter plot obtained between DBMS and logarithm of Heat Flow showing the low correlation and scattering between the data.

The normality in the data is very helpful in bivariate statistics, and for this reason, we removed the outliers and repeated the bivariate statistics showing a better Pearson's correlation but worst Spearman´s correlation and Kendall´s correlation (Table 1), nevertheless, the correlation coefficients are still below the 0.30 and the scatter plot is very dispersed (Fig. 6). From the results showed in the Table 2 and Table 3 we found low correlation between DBMS and heat flow in Mexico.

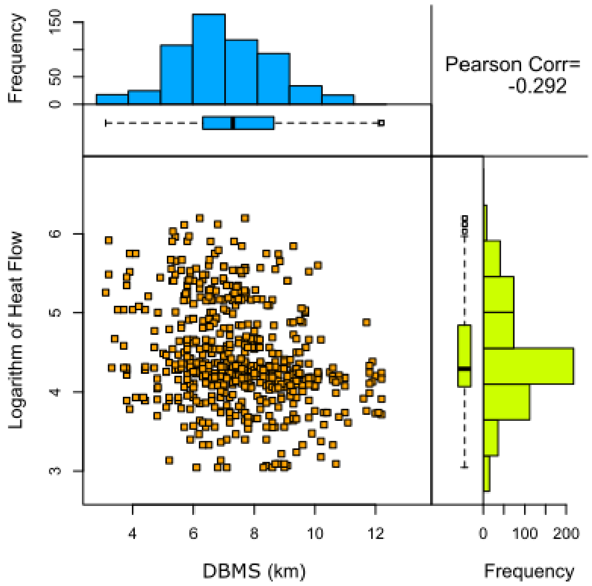

Figure 6: Scatter plot obtained between DBMS and logarithm of Heat Flow after removing the outliers.

4. CONCLUSIONS

Different physical features could be affecting the correlation between DBMS and heat flow, these features are listed below.

1.- Changes in the lithology: A rock sequence of magnetic minerals above the non-magnetic rock, as volcanic rocks above limestones, could estimate a DBMS related with a lithological change not with a CTD.

2.- Analysis window size: This study uses windows of 64 x 64 km expecting shallow values of DBMS. This window size works well in zones with geothermal activity, nevertheless, zones with a low thermal activity the values of DBMS associated to the DCT needs greater window size of almost 225 x 225 km for an estimated depth of 45 km (Rosales-Rodriguez 2014). The heterogeneity of the geological provinces shows the necessity to use variable window size depending on the geology of the zone as we see in some studies (Ross et al., 2006; Bouligand et al., 2009).

3.- Heat transfer mechanism: The main heat transfer mechanism in the crust is the conduction, nevertheless, in zones with high hydrothermal activity the convection is the main heat transfer mechanism, such as the case in Acoculco, where the estimation of the geothermal gradient could be affected by the presence of high permeability strata that host intense convection (Figure 7). Heat generation affects this relation, nevertheless, our results could not be affected by radiogenic heat generation because most of the heat flow data are clustered in zones associated to petroleum activities, that is, sedimentary basins with a broad distribution of limestones without radiogenic elements.

From the results obtained and the analysis of the physical features that affect the estimation of the DBMS, we conclude that a preliminary geological study is necessary using the main geological and tectonic features to deduce the parameters that may be affecting the relation between heat flow and DBMS.

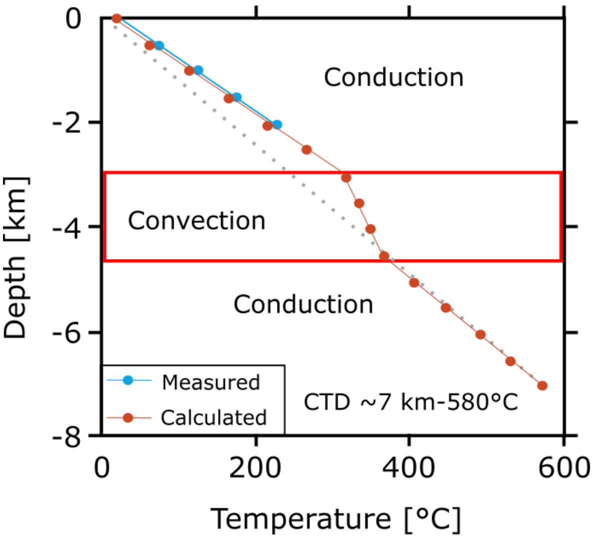

Figure 7: Conductive and convective heat transfer mechanism that affect the geothermal gradient estimation using the DBMS. Data from the well EAC1 from Acoculco, Mexico.

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TABLES

Table A: Univariate Statistics from the exploratory dana analysis.

	DBMS	Heat Flow	Logarithmic transformation of Heat Flow
n	618	618	618
Min.	2.50	13.00	2.56
First quartile	6.30	58.32	4.07
Median	7.40	73.00	4.29
Mean	7.56	127.84	4.47
Third quartile	8.70	136.21	4.91
Max.	16.30	1781.35	7.49
Variance	3.69	30264.06	0.61
Std. deviation	1.90	173.96	0.78
Asymmetry coefficient	0.50	5.60	0.718
Kurtosis	3.93	44.30	4.20

Table B: Correlation coefficients calculated between the logarithm of Heat Flow and DBMS.

Correlation Coefficient	Value
Pearson	-0.277
Spearman	-0.306
Kendall	-0.206

Table C: Correlation coefficients calculated between the logarithm of Heat Flow and DBMS after the outliers removing.

Correlation Coefficient	Value
Pearson	-0.292
Spearman	-0.291
Kendall	-0.192