Integration of heat flow measurements and estimations in the construction of Mexico's heat flow map

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ABSTRACT

Determination of the geothermal potential is linked to the heat transfer regime, which is related with the surface heat flow. Heat flow and temperature gradient data are very valuable to define the geothermal resources location. Presently, heat flow maps of Mexico lack detailed information due to the sparse available temperature gradient measurements. The Mexican Centre for Innovation on geothermal energy has carried studies to complete detailed maps of heat flow and thermal gradient that can be used to evaluate the geothermal resources of the country and to provide the location of favorable areas to developers.

Here, we present the integration of various data sets that contain measurements of diverse geophysical and geochemical parameters that allow estimation of heat flow. Principal component analysis (PCA) was the method used to combine the diverse data layers, PCA are commonly used with spatial data to identify combinations of variables that best explain the variance in the multivariate data. In addition to reducing dimensionality and colinearity, the results obtained with PCA yield more robust and simpler regression models.

In this work we include temperature gradient measurement in wells and silica concentration in water samples from springs and wells to create a more complete heat flow map for Mexico. All data are integrated to define the main anomalies that indicate the location of areas with high temperatures at relatively shallow depth. The obtained results show a good correlation in the location of high temperature anomalies in both data sets.

1. INTRODUCTION

Heat flow data based on actual temperature gradient in wells are rather scarce in Mexico (Prol-Ledesma, 1991). A thorough compilation of reported data was accomplished for this work, which yields more than 170 data for the continental territory of Mexico and 749 data ocean bottom heat flow measurements. Additionally, 331 transient bottom hole temperature measurements have been corrected to calculate the thermal gradient mostly in oil wells. The abundance of thermal springs in Mexico favored the collection of silica concentration data, this concentration has been used to calculate surface heat flow in 596 sites based on an empirical relationship calculated taking into account the available heat flow measurements in wells and the geological provinces (Prol-Ledesma and Juárez, 1986). Some thermal springs also have an intense gas discharge and helium isotopes ratio has been measured (Polak et al., 1985; Prasolov et al., 1999) to calculate heat flow by an empirical relation (Polak, 2005). The different data bases produced heat flow maps that contain similar patterns but their integration requires analysis of data set similarity.

It has been demonstrated that heat flow maps can be constructed based on different geological and geophysical parameters (Goutorbe et al., 2011), the relation has been obtained for heat flow and heat production, upper mantle structure, recent tectonic activity, magnetic data, mantle degassing and its channels to the surface, and groundwater flow patterns. These parameters are closely related to those utilized in this work: mantle degassing-helium isotopic ratio, groundwater flow patterns-silica temperature in hot and warm springs, magnetic data-Curie temperature depth. The measured and estimated heat flow data can be used to calculate the thermal gradient, assuming a conductive regime. The resulting deep temperature maps are important parameters in regional geothermal exploration by providing data on depth where temperatures reach values that are within the ranges of economic exploitation with presently available technology. However, results have to be validated with statistical method to insure their accuracy

The relationship between different parameters is dependent on the geological variability. The complexity in the surface geology and tectonic settings along Mexico made it important to analyze the behavior of the parameters within each geologic-tectonic province. The reported terranes in Mexico (Sedlock et al., 1993) that represent the predominant tectonic regimes for different areas are characterized by distinct thermal regimes (Fig. 1). Calculations for each terrane provided general correlations and the characteristic stratigraphic columns guided the selection of the average thermal properties of the crustal rocks.

Figure 1: Tectonostratigraphic terranes in Mexico. After (Sedlock et al., 1993).

Merging of the data can be attained by applying diverse methods, for instance: similarity and best combination procedures (Goutorbe et al., 2011). However, statistical analysis of the data is important in order to establish the correlation of the multiple data set. Therefore, a multivariate scheme was chosen to create a map that includes the information from the available data sets on heat flow values measured in wells and those calculated from silica temperature.

2. METHODOLOGY

In addition to the direct measurements of temperature gradient in wells, surface heat flow was also calculated using the silica concentration in water from hot and warm springs. Numerous springs were sampled and silica geothermometer (Fournier, 1977) was applied where sodium-chloride or bicarbonate water was discharged by the springs. Previous studies have calculated an empirical relationship between silica temperature and heat flow (Swanberg and Morgan, 1979, 1980) according to equation [1]:

$$T\ SiO2 = mq + b \qquad [1]$$

where b is the local mean annual temperature, and the product of the slope m times the thermal conductivity is related with the groundwater circulation depth (Swanberg and Morgan, 1980). The value of those constants has been calculated for Mexico as: m=518°C m^2W^{-1} and b=41°C (Prol-Ledesma and Juárez, 1986). Additionally, some local studies have increased the number of estimated heat flow values for northern Mexico (Marvin, 1984; Beltrán-Abaunza and Quintanilla-Montoya, 2001).

2.1 Principal Component Analysis

Raster maps were created by interpolation of the heat flow measurements and the heat flow calculations from silica temperature. They were used as input variables in the principal component analysis (PCA). This method has been widely utilized when multivariate spatially referenced data are to be combined to obtain fewer synthetic variables that explain the observed variance of a system, still keeping all the relevant information contained in the original data sets. By maintaining the statistically significant information the resulting map will include the dominant patterns that can be used in regional exploration.

The correlation of the two variables in similar geological settings was tested by extracting the data for the Trans-Mexican Volcanic Belt (TMVB) province, where data are more abundant than in other regions. Variance-covariance and correlation matrices were calculated for both variables.

3. RESULTS AND DISCUSSION

Two maps were constructed with heat flow measurements and the heat flow estimations calculated with the silica temperature for the TMVB province and then integrated in one map (Fig. 2).

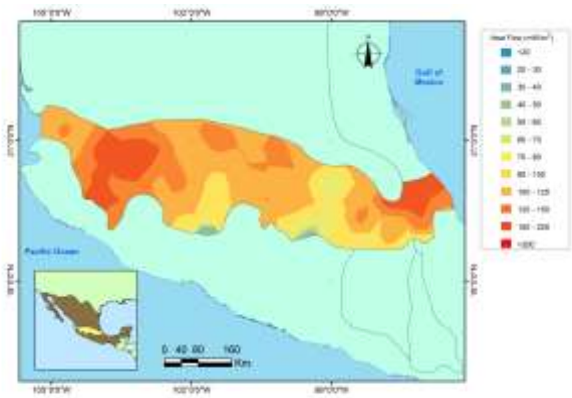

Figure 2: Heat flow measurements and estimations interpolation in the TMVB province

Calculation of the correlation matrix shows a positive correlation between heat flow measurements and silica temperature calculations of more than 47% which is higher than that obtained by Swanberg and Morgan (1979) for the linear regression for 1° x 1° blocks in the United States.

The spatial correlation obtained for both sets of data in the TMVB province was extended to the whole country and a more complete map was obtained by combining measurements and calculations (Fig. 3).

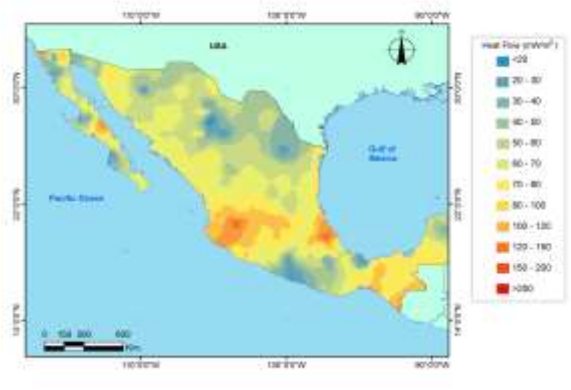

Figure 3: Integration of heat flow data and calculations based on measurements and silica temperature interpolation

This map was used to calculate the geothermal gradient by assuming an average thermal conductivity of k = 2.6 W/m°C that would be an average between igneous and sedimentary rocks (Stacey, 1977; Popov et al., 2011) accordingly to the stratigraphic data for the geological terranes in México (Sedlock et al., 1993). This calculation is based on the assumption of conductive heat transfer on a regional scale.

The values obtained for the geothermal gradient indicate that in large areas the gradient is higher than the conventional value of 30 ºC/km. These values have to be considered in the regional scale and local variations are expected due to limited effects where heat transport includes an important convective effect.

The temperature gradient values were used to calculate the temperature that would be expected at a depth of 1000 m. The results indicate that large areas present temperatures above 100ºC at depths shallower than 1000 m. This temperature can be considered as the lowest limit for binary cycle production of electricity

By applying the PCA method for multivariate integration of data, general patterns in the heat flow can be shown in one map. The most important result of a regional heat flow map is the calculation of the deep temperatures, which is a key parameter in geothermal exploration.

4. CONCLUSIONS

The maps constructed with the integration of two data sets show patterns where high heat flow anomalies define important regions for further investigation on regional exploration of geothermal resources: Chiapas and Oaxaca in southern Mexico, the central and southern areas of the Baja California Peninsula, and by far the most interesting part is the western region of Mexico. Specifically, in Chiapas there is a lack of heat flow measurements but this deficiency can be overcome by the silica-heat flow estimations that are abundant due to the numerous hot springs that have been sampled. The same situation happens in the TMVB and the Sierra Madre Occidental that probably host important geothermal resources still to be discovered.

REFERENCES

Beltrán-Abaunza, J.M. and Quintanilla-Montoya, A.L.: Calculated Heat Flow for the Ensenada Region, Baja California, Mexico. Ciencias Marinas, **27**, Ensenada, (2001), 619-634.

Fournier, R.O.: Chemical geothermometers and mixing models for geothermal systems. Geothermics, **5**, Amsterdam, (1977), 41–50.

Goutorbe, B., Poort, J., Lucazeau, F., Raillard, S.: Global heat flow trends resolved from multiple geological and geophysical proxies. Geophys. J. Int., **187**, Hoboken, (2011), 1405–1419.

Marvin, P.R.: Regional heat flow based on the silica content of ground waters from northcentral Mexico. M. Sc. Thesis. New Mex. St. Univ., 107 pp. (1984).

Polak, B.G.: Heat and mass transfer from the mantle: heat flow and He-isotope constraints, Annals of Geophysics, **48**, Bologna, (2005), 9-17.

Polak, B.G., Kononov, V.I., Prasolov, E.M., Sharkov, I.V., Prol-Ledesma, R.M., González, A., Razo, A. and Molina-Berbeller, R.: First estimations of terrestrial heat flow in the TMV and adjacent areas based on isotopic composition of natural helium, Geofís. Int., **24**, Mexico, (1985), 465-476.

Popov, Y., Romushkevich, R., Korobkov, D., Mayr, S., Bayuk, I.,Wilhelm, H.: Thermal properties of rocks of the borehole Yaxcopoil-1 (Impact Crater Chicxulub, Mexico). Geophys. J. Int. **184**, Oxford, (2011), 729–745.

Prasolov, E.M., Polyak, B.G., Kononov, V.I., Verkhovskii, A.B., Kamenskii, I.L. and Prol, R.M.: Inert gases in the Geothermal Fluids of Mexico. Geochemistry International, **37**, Berlin, (1999), 128-144

Prol-Ledesma, R.M.: Heat Flow in Mexico, in: Terrestrial Heat Flow and the Lithosphere Structure. Cermak, V. and Rybach, L., (Eds) Springer Verlag, Berlin-Heidelberg, 475-485, (1991).

Prol-Ledesma, R.M. and Juárez, G.: Geothermal Map of Mexico. Journal of Volcanology and Geothermal Research, **28**, Amsterdam, (1986), 351-362.

Sedlock, R. L., Ortega-Gutiérrez, F. and Speed, R. C.: Tectonostratigraphic terranes and tectonic evolution of Mexico. Geological Society of America. Special Papers 278, 153 pp. Boulder, (1993).

Stacey, F.D.: Physics of the Earth 2nd edition, Wiley, New York, (1977), 414 pp.

Swanberg, Ch.A. Morgan, P.: The linear relation between temperatures based on the silica content of groundwater and regional heat flow: a new heat flow map of the United States. Pure Appl. Geophys., **117,** Heidelberg, (1979), 227--241.

Swanberg, Ch.A. Morgan, P.: The silica heat flow interpretation technique: Assumptions and Applications. J. Geophys. Res., **85**, New York, (1980), 7206--7214.

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