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REGIONAL EXPLORATION OF GEOTHERMAL RESOURCES USING SILICA GEOTHERMOMETER/HEAT FLOW

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ABSTRACT

Regional exploration is focused on the discovery of thermal anomalies that will guide more detailed exploration. Heat flow data define surface evidence of geothermal manifestations. However, they are not very common and other information can be used to guide reconnaissance exploration. Mexico has few areas where geothermal exploration has been performed, but still large areas remain unexplored. Heat flow data do not cover the whole country, therefore we used silica-temperature information to complement the information gaps; however, calculation of heat flow using silica geothermometer data is not reliable thought the equilibrium temperature is valuable to approximate the geothermal potential of a prospect.

Silica concentration in spring/well water is indicative of temperature at depth, provided chemical equilibrium is attained, which is not always the case. Furthermore, a parameter that remains elusive is the equilibrium depth, which hinders an accurate calculation of thermal gradient. The relation between silica geothermometer and heat flow is only qualitative, generally the correlation coefficient obtained for heat flow and silica temperature data is <50% and should not be used as an exact heat flow determination to be included in thermal models. Previous work tried to establish a relationship using multivariate statistics to heat flow and silica temperature datasets and a better correlation was obtained for geologically homogeneous areas (Prol-Ledesma et al., 2016). However, the calculation of silica temperature in samples from water wells and springs provide regional information of temperature at depth that may be useful in defining prospective areas for regional exploration.

Multivariate statistical analysis of both data sets points to anomalous heat discharge areas defined by different methodology that will be useful to guide local exploration. This approach has been successful in defining new areas to widen the possibilities of exploitation of geothermal potential in Mexico: as southern Baja California Peninsula, the northern part of the Sierra Madre Occidental and the continuation in the continent of the Orozco fracture zone.

1. INTRODUCTION

Heat flow measurement is highly relevant for the regional evaluation of the geothermal potential. However, temperature logs and thermal conductivity data are not easily accessible because deep wells available for stable temperature measurements and core samples to measure conductivity are scarce. The need of heat flow data has prompted the elaboration of methods to estimate heat flow through parameters that do not involve continuous deep well temperature logging and core recovering, for instance: deep temperature calculation using geochemical geothermometers, Curie temperature depth, ^{3}He/^{4}He radio in gases discharged by hydrothermal surface manifestations, BSR depth and surface temperature calculation based on radiant energy detected with multispectral. All these methods present large uncertainties in the evaluation of the geothermal gradient because determination of the temperature-depth relation is not accurate.

Heat flow data produced with actual temperature well logs is the most reliable source of information to evaluate the depth at which adequate temperature for geothermal resources exploitation or utilization is attained. The geothermal resources of Mexico are still far from being fully exploited and a reliable heat flow map should point out the most relevant prospects to explore in the near future. The methods to estimate heat flow must be properly validated before including estimated values in a measured heat flow map. However, some methods derive deep temperature estimations that may be useful to mark high heat discharge anomalies, even if accurate calculation of heat flow is not attainable. Each estimation method generates uncertainty about the actual information obtained with the specific calculation and proper evaluation of the conditions required to insure accuracy is needed before accepting estimation as actual heat flow values. Previous evaluation of silica geothermometer values in the evaluation of heat flow yielded a low correlation coefficient <40% (Prol-Ledesma and Juárez, 1986), which is similar to that obtained in other regions (Swanberg and Morgan, 1978, 1980; Swanberg et al., 1981; Marvin, 1984; Pirlo, 1984) and some authors assumed that the reliability of the heat flow estimate is expected to improve as more silica data become available (Marvin, 1984).

Here, we present a critical evaluation of the silica geothermometer method to estimate heat flow in regional studies at country level and analyse the usefulness of the silica geothermometer data to define prospective geothermal provinces.

2. HEAT FLOW IN MEXICO

Mexico's vast geothermal resources are evident from the heat flow map (Prol-Ledesma et al., 2018). Large continental areas in Mexico present heat flow values higher than 100 mW/m^2, which are significantly higher than 67.7 mW/m^2, which is the mean value for continents, as reported by Davies and Davies (2010).

The heat flow map of Mexico (Fig. 1) shows a large area contained within the 100 mW/m^2 contour line, which includes the Mexican Volcanic Belt, the Gulf of California extensional province and the large areas in central Mexico that are characterized by recent alkaline volcanism (Prol-Ledesma et al., 2018). The increase in the number of heat flow values will allow a more reliable identification of new geothermal prospects, because presently the heat flow measurements coverage is not as dense as to allow confident identification of specific new geothermal areas. Therefore, other parameters should be used to allow detection of hydrothermal systems with favourable conditions for exploitation/utilization.

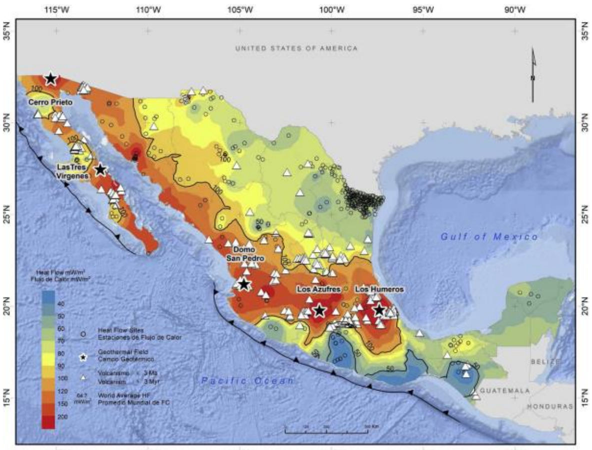

Figure 1: Heat flow map of Mexico (Prol-Ledesma et al., 2018). The 100 mW/m^2 contour is outlined to mark the areas with a high geothermal potential.

2.1 Geothermal fields and heat flow

Geothermal fields currently in exploitation are restricted to the areas with heat flow >200 mW/m^2 (Fig. 1); however, large areas with heat flow >100 mW/m^2 remain largely unexplored. Frequently, those areas coincide with the occurrence of recent volcanic activity (Prol-Ledesma and Morán-Zenteno, 2019), and other parameters could support selection of favourable areas for reconnaissance/detailed exploration work. An important parameter to define prospective areas could be silica temperature calculated in hot and warm springs samples, which are abundant in all the country (Fig. 2).

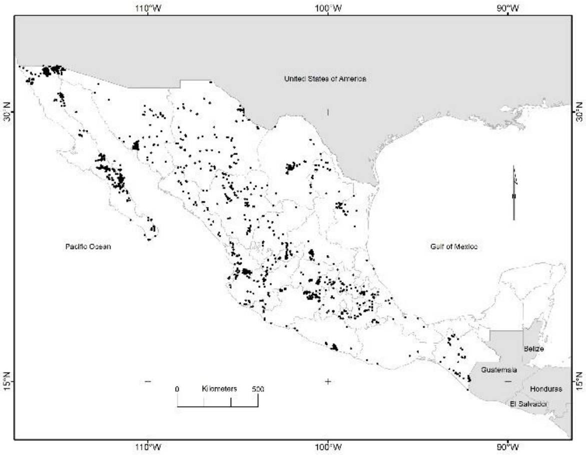

Figure 2: Thermal springs where silica concentration has been determined. The silica concentration was used to calculate equilibrium temperature using the silica geothermometer.

3. SILICA TEMPERATURE

Silica concentration in thermal spring water is indicative of the equilibrium temperature at depth. The correctness of this value to express the heat discharge depends on several factors: most important is the equilibrium attainment, which is frequently achieved in the reservoir; however, as reservoir water ascends to the surface, numerous phenomena may occur, as boiling and mixing, in addition to the water-rock interactions that may take place in shallow aquifers. Mixing is a typical process that commonly reduces silica concentration and caused the underestimation of the temperature at depth. A key parameter in the association of silica temperature and heat flow/geothermal gradient is the depth at which equilibrium takes place. Therefore, even in the case that equilibrium is attained, and minimal mixing occurs at the hydrothermal upflows, evaluation of the geothermal gradient is hindered by the unknown depth.

3.1 Silica temperature data

Silica concentrations are easily available for most thermal springs reported in Mexico Figure 2 shows the location of all thermal springs where silica concentration has been determined; many of these data were obtained from published papers but some data were determined during surveys sponsored by the CeMIE-Geo P-01 project.

A total of 929 silica concentration data we used to construct the map presented in Figure 3. Temperature calculation was performed following indications from Karingithi (2009) to apply the equations for the different silica polymorphs: quartz (conductive and steam loss), chalcedony and amorphous silica.

3.2 Silica temperature map

The distribution of thermal springs where silica temperature can be calculated has a better coverage than heat flow measurements (Fig. 2). The presence of thermal springs is related to the high heat flow in most areas and reveals the possibility of exploitation and utilization of the geothermal resources. Interpolation of the silica values, using the IDW algorithm produces a reliable silica temperature map (Fig. 3) that is directly related to surface manifestations that are linked to hydrothermal activity at depth. Most areas area characterized by temperatures higher than 100ºC, which would allow a variety of direct utilization applications and, in some cases, electricity production with binary plants.

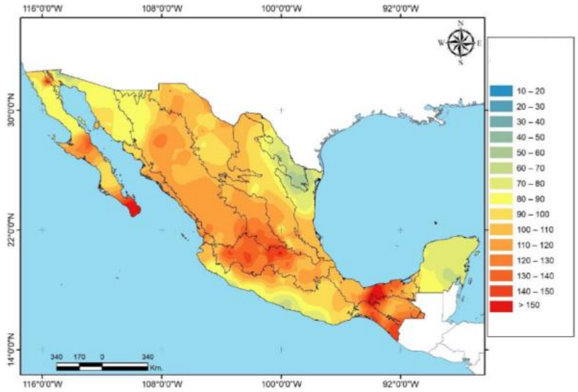

Figure 3: Silica temperature map (T_{SiO2} ºC), silica concentration measured in water samples from thermal springs and water wells.

3.3 Silica temperature and heat flow

A direct relationship between silica geothermometer calculated temperature and heat flow has been assumed to be valid in many geothermal regional studies (Swanberg and Morgan, 1978; 1980; Marvin, 1984; Prol-Ledesma and Juárez, 1986; Beltrán-Abaunza and Quintanilla-Montoya, 2001). However, the correlation coefficient in most studies is lower than 50% and this low correlation has been attributed to the typical processes that affect the determination of an accurate deep equilibrium temperature using chemical geothermometers: mixing and boiling processes, re-equilibration in shallow aquifers, data scarcity, etc.

Here, we used a good coverage of silica temperatures distributed in most geological provinces in Mexico (Fig. 2) and a better heat flow coverage than in previous studies. Nonetheless, the statistical analysis of both data sets indicates that the correlation between heat flow and silica temperature does not improve and remains below 50%. This complex relation between heat flow and thermal springs was also noted previously in country-wide studies in the USA and Australia (Pirlo, 2002; Ferguson and Grasby, 2011).

3.4 Statistical analysis of silica temperature and heat flow relation

The statistical analysis of the relation between silica temperature and heat flow data indicate that the main problem for correlating the available data in Mexico is the distribution of both sets of data in two cases: distribution in physiographic provinces and geographic 2° x 2° areas. In both cases the data distribution is not uniform, and the data are grouped according to different patterns: heat flow measurements are constrained to the presence of wells, mostly related with oil production or water wells, and silica temperatures are restricted to the occurrence of hot/warm springs. Therefore, the increase in the number of measurements does not improve the correlation between both sets of data.

4. CONCLUSIONS

Heat flow and silica temperature provide evidence of high anomalies of heat discharge in the crust; however, the relation between both parameters remains qualitative, even after an almost 10-fold increase in the number of heat flow measurements and a 6-fold increase in the silica temperature data. However, the qualitative integration of both data sets with the local geological and tectonic setting allows to define prospective areas that are highly favourable to pursue detailed geothermal exploration.

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