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First Assessment of the State of Queretaro (Mexico) Geothermal Reserves

Eduardo R. Iglesias, Rodolfo J. Torres and J. Ignacio Martinez Estrella

Instituto de Investigaciones Electricas, Reforma 113, 62490 Cuernavaca, MOR., Mexico

iglesias@iie.org.mx

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ABSTRACT

As we have shown in previous work, there are important geothermal reserves with temperatures below 200°C in Mexico, which are mainly sub-utilized. Our previous work focused on the aggregated reserves of the whole country. In this paper we present a first, partial assessment of the geothermal reserves of the State of Queretaro. This assessment is necessarily partial because the information currently available is insufficient to estimate the reserves of the whole state. Queretaro is the second Mexican state, when considering the number of known geothermal localities by state. Our updated compilation registers 238 geothermal localities (warm springs and domestic water wells) in it. This abundance of geothermal resources is consistent with the fact that 50.6% of the state's area lies on the Mexican Neovolcanic Axis. Our present reserve assessment includes 112 (47%) of the cataloged geothermal localities. These are distributed in 28 geothermal systems with areas ranging between 3 and 46 km^2. To estimate the reserves we used the volume method, complemented with Monte Carlo simulations, to quantify the inevitable uncertainties, and a recovery factor equal to 25%. Our results indicate that the reserves corresponding to these 28 geothermal systems lie between 1.9x10^4 and 3.3x10^4 PJ, with 90% confidence. The most likely estimated reservoir temperatures range 77-161°C. These temperatures are adequate for an ample variety of domestic and industrial direct heat applications that would be useful for the socioeconomic development of the State. Some applications suggested by the current economic activities in the State are: drying fruits, grains and cement blocks; process heat for the textile, paper, sugar, beer and soft drinks industries; greenhouses; fish farming; space heating and refrigeration; spas and other touristic attractions. The magnitude of these reserves and that of their associated temperatures are potentially important to positively impact the economic development of the State, in particular, that of the human populations co-localized with the geothermal systems. In the near future we plan to obtain the information missing to allow the assessment of the reserves corresponding to the identified localities that currently lack these data.

1. INTRODUCTION

Our group has been involved in assessing the medium- to low-temperature geothermal reserves of Mexico for the last several years. First we published a report (Iglesias and Torres, 2003) that included the aggregated results of our reserve estimates for 276 geothermal systems spread over 20 Mexican states. Next we published our estimations of the individual geothermal reserves of these 20 Mexican States (Iglesias and Torres, 2005). Since the publications just mentioned, we have significantly updated our database (Torres *et al*. 2005) and developed a GIS-based information system to help assess geothermal reserves (Martinez-Estrella *et al*., 2005). The present assessment includes the new data.

The state of Queretaro is located near the geographic center of Mexico, and covers an area of 11,558 km^2. Three different physiographic provinces converge on its territory (Fig. 1). The Sierra Madre Oriental covers the northeastern part of the state; the Mesa Central covers a fraction of the western part of the state; and the Trans-Mexican Volcanic Belt overlays the southern part of its territory (Fig. 1).

Queretaro has abundant geothermal resources. Our database catalogs 238 geothermal localities (individual warm springs and domestic water wells) in the State, which produce fluids with surface temperatures in the 28-42°C range. At least 15 thermal water spas have been catalogued in the State. All these geothermal localities lie on the Trans-Mexican Volcanic Belt physiographic province, which covers 50.6% of the State´s area (Fig. 1). Note that the selection of the catalogued geothermal localities is biased by their proximity to roads and railroad (Fig. 1).

In the following sections we briefly describe the method utilized for reserve assessment and the corresponding data. Then we discuss our results, and present our conclusions.

2. METHOD

Following Muffler and Cataldi (1978), we chose the volume method for the present reserve assessment. With this method one first calculates the thermal energy contained in a given volume of rock and water, and then how much of this energy is recoverable. The thermal energy is calculated as (Brook et al., 1978):

$$q_R = \rho_C \, A \, h \, (T - T_{ref}) \qquad (1)$$

where q_R = reservoir thermal energy in kJ, ρ_C = volumetric specific heat of rock plus water (2700 kJ/m^3 °C), A = reservoir area (m^2), h = reservoir thickness (m), T = mean reservoir temperature (°C), and T_{ref} = reference temperature (local mean annual temperature, °C). The volumetric specific heat was calculated assuming the rock volumetric specific heat to be 2,500 kJ/m^3 °C and the reservoir porosity to be 15 percent. Since most of the heat is stored in the rock (e.g., Grant et al., 1982), our estimates depend only weakly on the magnitude assumed for the porosity.

In order to quantify the uncertainty in the reserve assessments, we used statistical methods in the calculation of the thermal energies, following Brook et al. (1978) and Natheson (1978). The uncertainty in the thermal energy results mainly from the uncertainties in the values estimated for A, h, T and T_{ref}. With the exception of T_{ref}, these values result from an educated judgment based on geology, geophysics, geochemistry, down-hole measurements and geothermometry. The uncertainty in the reference temperature arises from using regional long-term averages that, for topographic or other reasons, may differ significantly from local mean temperature.

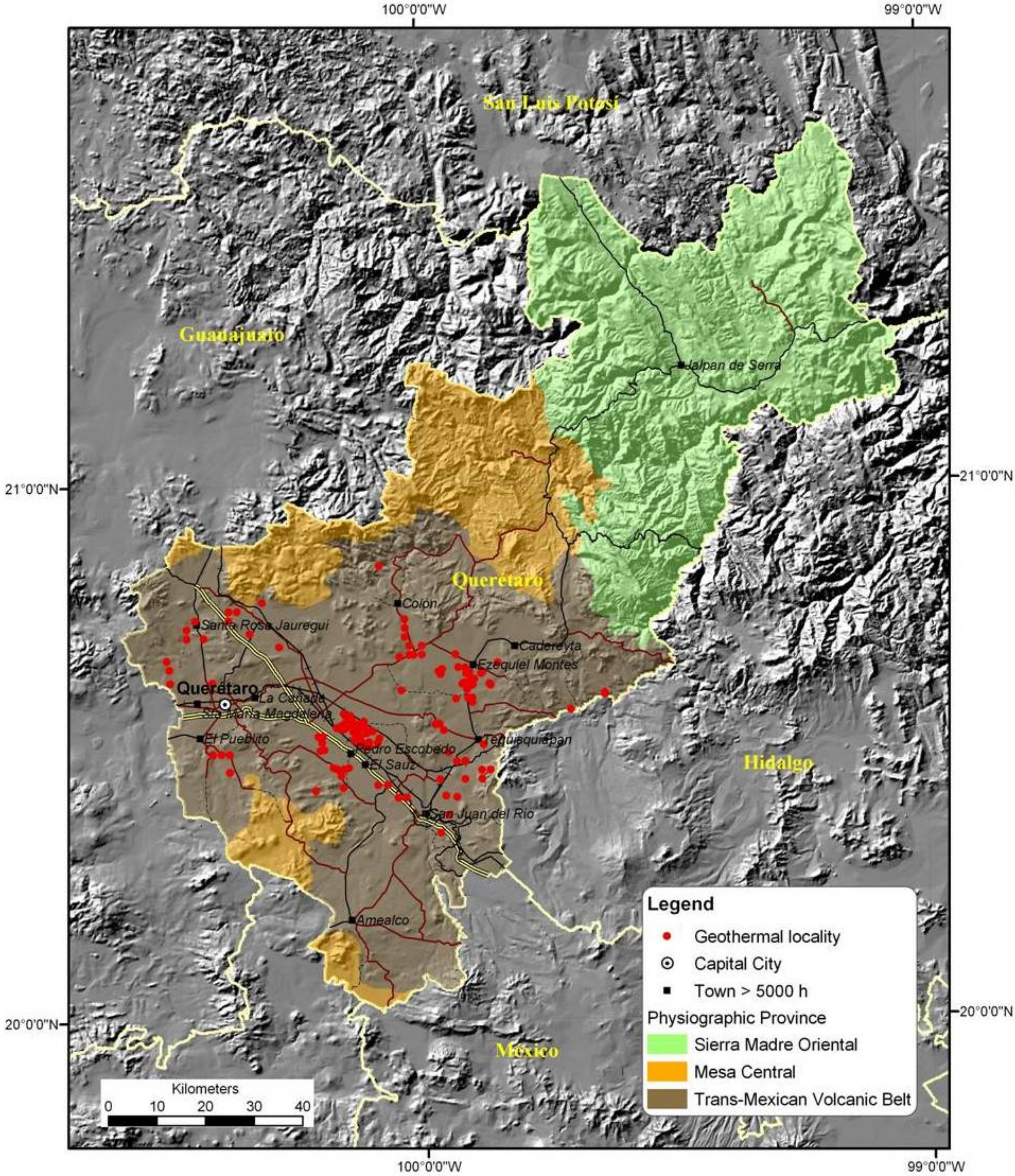

Figure 1: Physiographic provinces in the State of Queretaro and catalogued geothermal localities

To determine the uncertainty in these estimates we assume, for each of these input variables, a triangular probability density that represents our subjective judgment of the true probability density. As an example, let's take the variable reservoir temperature (Fig. 2). The parameters in Fig. 2 are defined as: T_1 = minimum reservoir temperature; T_2 = most likely reservoir temperature; T_3 = maximum reservoir temperature. The mean $\check{T}$ and standard deviation σ_T are also represented. The area of the solid vertical band gives the probability that the characteristic reservoir temperature lies between the values T and $T + \Delta T$.

We use these triangular probability densities to compute the probability densities of the thermal energy for each geothermal locality, as defined in equation (1), by means of the Monte Carlo method. In this way we obtain histograms and fits, and a variety of statistics that include mean, mode, median, standard deviation, variance, etc. Thus, we can determine confidence intervals for the estimated thermal energy. In this way, we quantify the uncertainty in this inferred variable.

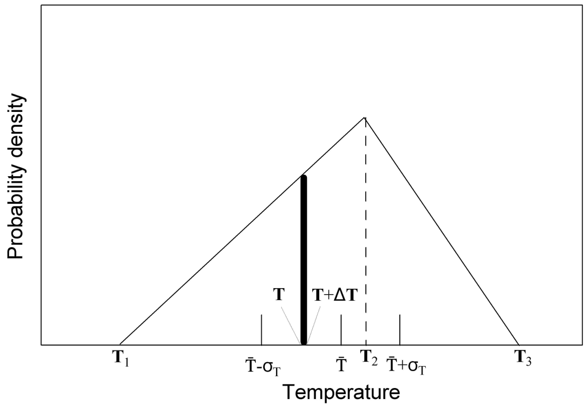

Figure 2: Example of triangular distribution for reservoir temperatures

Using the Monte Carlo method to compute the thermal energy of individual geothermal systems we have significantly improved the method used by previous authors (Brook et al., 1978). These authors used products of mean values of area, thickness and the difference between mean values of T and T_{ref} to compute mean values of thermal energy for individual localities. Multiplication of mean values is valid only if the variables A, h and T are statistically independent in the reservoir considered. A statistical dependence of some or all of these variables in the reservoir can hardly be discarded. Using the Monte Carlo method removes the necessity to assume statistical independence of the variables.

After computing the probability densities of the thermal energy for the individual geothermal systems included in this assessment, we calculated, from them, the probability density of total thermal energy corresponding to all the systems. This problem is analytically intractable (Natheson, 1978). We therefore again used the Monte Carlo method to compute the distribution of total thermal energy. This entailed first fitting analytical probability densities to the 28 computed distributions of local thermal energy, and then running a Monte Carlo simulation with them. Having obtained this distribution we were then able to derive confidence intervals to evaluate the uncertainty associated with the total thermal energy.

Monte Carlo simulations produce sample distribution functions that converge to the true distributions as the number of iterations increases. By trial and error we arrived at 5,000 iterations as the optimal number to use in each Monte Carlo simulation: higher numbers of iterations (we tried 500 to 10,000) resulted in minimal changes in the results.

Reserves are estimated as the fraction of identified stored accessible thermal energy legally and economically producible today with current technology. The usual approach is to estimate reserves as the product of the stored thermal energy times a so-called recovery factor R. This factor summarizes the physical and technological constraints that prevent all the thermal energy in the reservoir from being extracted. Following Bodvarsson (1974), Natheson (1975), and Natheson and Muffler (1975), we assumed a constant value of 0.25 for R in our reserve estimates, as a first approximation. We did not attempt to estimate the uncertainty of R, which depends on a number of variables, and is case-pecific.

Finally, all figures derived in this paper should be regarded as order-of-magnitude estimates. However, they should be no less reliable than the published estimates of other energy resources, because they probably involve less speculation about unseen evidence (Armstead and Tester, 1978).

3. DATA FOR RESERVE ASSESSMENT

We obtained part of the necessary data from a database compiled and implemented in MS Access, by our workgroup (e.g., Torres *et al*., 2005). This database contains detailed information on 2,332 identified geothermal localities in Mexico, with sample temperatures greater than 28°C. The available information includes, for each geothermal locality, an identification alphanumerical code, geographical coordinates, state, municipality, local name, sample temperature, heat flow, six descriptive alphanumerical codes (listed below), and reservoir temperature inferred from five geothermometers. The descriptive codes indicate: (1) fluid type; (2) type of surface manifestation; (3) inferred heat source; (4) reservoir temperature class based on the SiO_2 geothermometer; (5) type of geothermal system; and (6) geological age of the production zone.

Our database catalogs 238 geothermal localities in Queretaro. They consist of warm springs and domestic water wells.

With the exception of the reference temperature and the value adopted for ρ_C (Section 2 above), we obtained or inferred, from this dataset, the necessary data for reserve assessment, as explained below.

3.1 Reservoir Areas

Accurate reservoir areas are difficult to obtain, even in well-studied geothermal reservoirs with extensive drilling in them. Where the only evidence of the existence of a hot-water reservoir is a single surface manifestation (spring, well), we assigned to it a most likely area A_2 = 2.688 km^2, defined by a circle of radius equal to 925 m. We also assigned it a minimum area $A_1 = 0.5\ A_2$ and a maximum area $A_3 = 1.5\ A_2$. International experience indicates these are reasonable assumptions (e.g., Brook et al., 1978).

Where the most likely areas of adjacent geothermal localities overlap (e.g., Fig. 3), we assumed the area of the resulting polygon as the most likely area of the corresponding geothermal system. And as before, a minimum area $A_1 = 0.5\ A_2$ and a maximum area $A_3 = 1.5\ A_2$ for the geothermal system. The polygon areas were automatically computed by means of the GIS information system developed by our group (Martínez-Estrella *et al*., 2005).

3.2 Reservoir Temperatures

In order to assign values to T_1, T_2 and T_3 for each locality, we adopted the following rules: *(a)* T_1 = the maximum of all the sample temperatures in the locality; *(b)* if the temperature indicated by any of the available geothermometers is less than T_1, do not consider that (these) geothermometer(s); *(c)* if after the previous filtering there are less than two geothermometer estimates left in a locality, drop this locality; *(d)* T_2 = average of all remaining geothermometer estimates plus sample temperature; *(e)* T_3 = maximum temperature indicated by available geothermometers.

3.3 Reservoir Thickness

We assumed a uniform thickness over the reservoir area, for simplicity. Following Brook et al (1978), the estimates in this assessment include thermal energy to a maximum depth of 3 km. Because of this, the reservoir bottom is assumed to be at 3 km unless there is evidence to suggest a shallower depth. If data from geophysical surveys or drilling provide any indication of the top of the reservoir, these data were used to estimate the thickness. Otherwise, a minimum depth of 0.5 km, a maximum of 2 km, and a most likely depth of 1.5 km to the top of the reservoir were assumed. Depths to the tops of reservoirs of drilled geothermal systems typically lie within this range. Therefore our standard thickness estimates are h_1 = 1,000 m, h_2 = 1,500 m and h_3 = 2,500 m. It is worth noting that for most reservoirs the uncertainties in the thickness are small compared to those of the area (Brook et al., 1978).

3.4 Reference Temperature

For the minimum, most likely and maximum reference temperature, we adopted long-term annual averages for the state of Queretaro, taken from the Mexican Instituto Nacional de Estadística, Geografía e Informática (INEGI, 2004) web page.

4. RESULTS AND DISCUSSION

A significant fraction (53%) of the 237 geothermal localities in our Queretaro database lack data on one or more parameters (e.g., geographical coordinates, sample temperature, not enough geothermometers) necessary to estimate the corresponding heat reserves. Thus we ended up with 112 geothermal localities to estimate the geothermal reserves of this State.

Using the criteria of the previous section we found that these 112 geothermal localities are grouped in 28 geothermal systems (Fig. 3). For each of these 28 systems our Monte Carlo simulations generated probability density distributions of the estimated reservoir thermal energy, and the statistical parameters mentioned in section 2. As an example of these results, Figure 4 presents the distribution corresponding to system LQRO006, which includes 37 geothermal anomalies.

Table 1 summarizes our results for the 28 geothermal systems. The corresponding most likely areas lie between 2.68 and 46 km^2. The most likely reservoir temperatures range from 77 to 161°C. These temperatures are potentially useful for a variety of applications within the socioeconomic environment of the state, such as drying fruit, lumber, cereal and cement blocks; concentration of fruit juice; milk evaporation; process heat for textile, paper, sugar, beer, soda, etc. industries; greenhouses; fish farming; and spas. The systems with higher temperature might be used for power generation as well.

There is a significant correlation between the number of geothermal localities included in the system and the mean of the corresponding probability density distribution of thermal energy, as illustrated in Fig. 5. In principle one should expect this, because more anomalies in the system tend to increase its area, and that increases the system's thermal energy (equation 1). Deviations about the correlation line of Fig. 5 are of course also due to differences in reservoir temperature, and reservoir thickness.

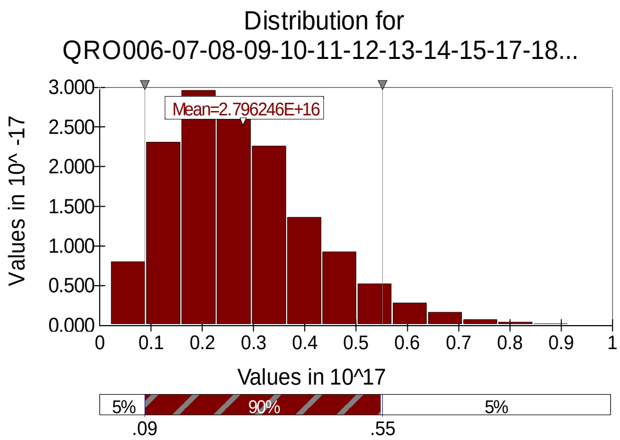

Figure 4: Probability density distribution of reservoir thermal energy (in kJ) for the geothermal system LQRO006. Note the 90% confidence interval and the distribution mean

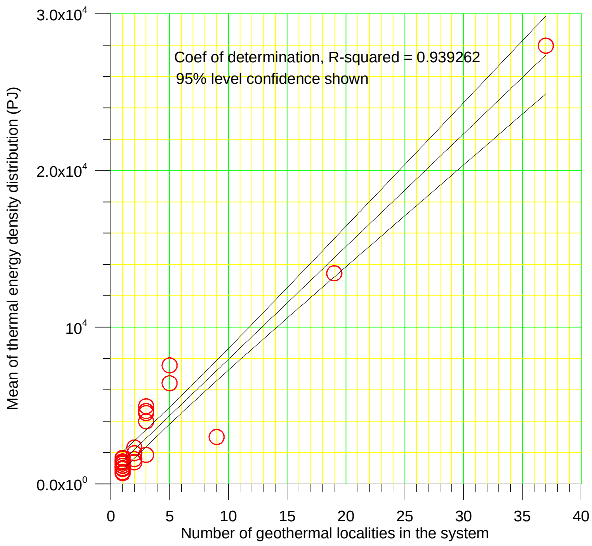

Figure 5: Correlation between the number of geothermal localities in the system and its thermal energy distribution mean

As mentioned in section 2, we also estimated the probability distribution of the aggregated thermal energy corresponding to the 28 systems by means of a Monte Carlo simulation, from the distributions of the individual systems. These results are shown in figure 6. The estimated total thermal energy is between 0.76 10^5 and 1.32 10^5 PJ, with 90% confidence. The main statistics of this distribution are: mean = 1.02 10^5 PJ, mode = 9.70 10^4 PJ, median = 1.00 10^5 PJ, standard deviation = 1.72 10^4 PJ, skewness = 0.5217.

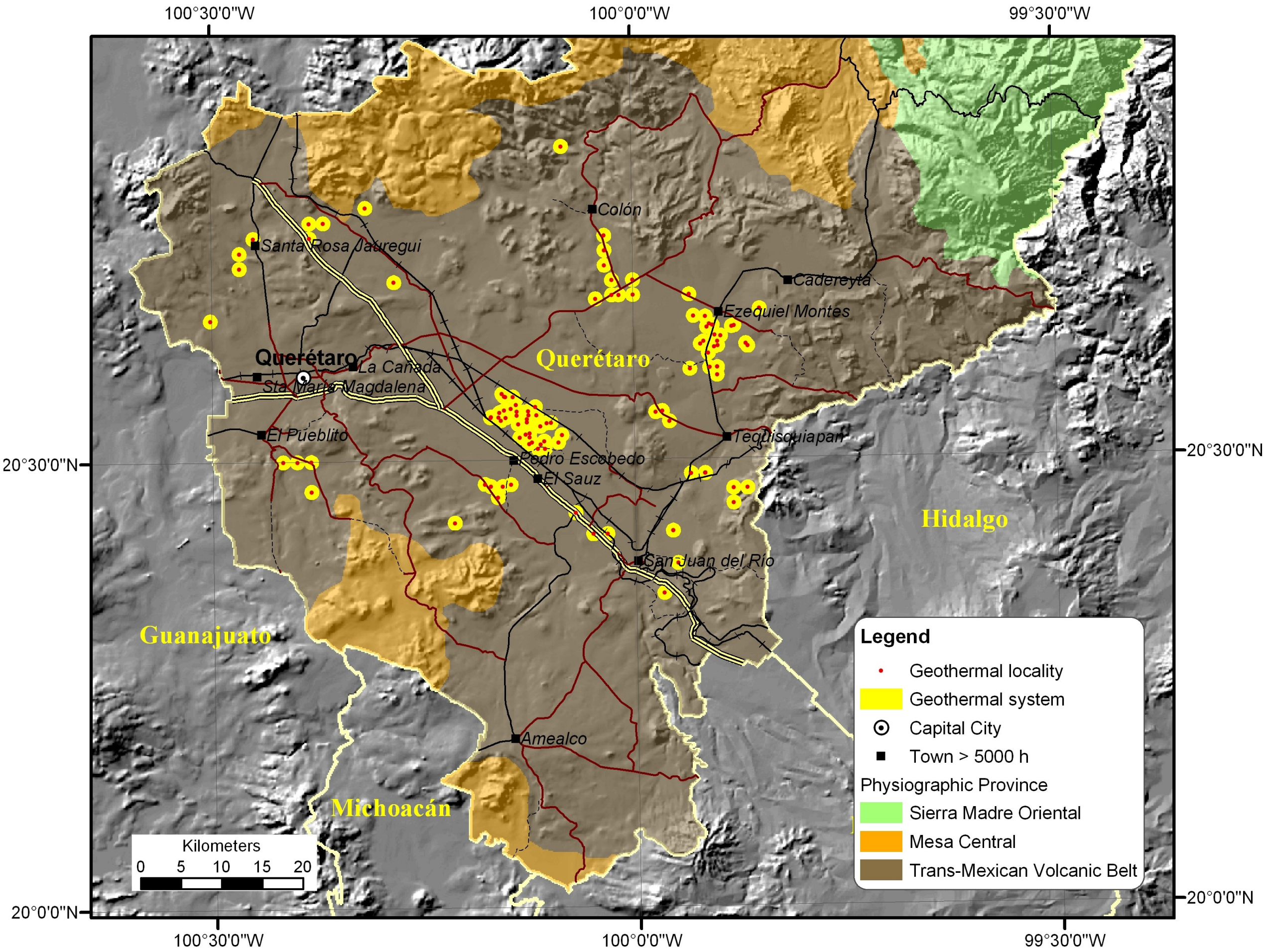

Figure 3: Location and areal extent of the 28 inferred geothermal systems with adequate data to estimate reserves

Table 1. Summary of Results.

Name geoth. system	No. of anomalies in system	System´s mean temperature (°C)	System´s thermal energy probability density - Mean and 90% confidence interval (PJ)		
			5%	Mean	95%
LQRO001	1	76.79	3.01E+02	6.80E+02	1.17E+03
LQRO002	1	84.00	3.40E+02	7.37E+02	1.26E+03
LQRO003	2	77.93	5.44E+02	1.37E+03	2.46E+03
LQRO006	37	129.18	8.79E+03	2.80E+04	5.51E+04
LQRO025	5	138.72	2.07E+03	6.42E+03	1.22E+04
LQRO036	1	126.10	4.64E+02	1.40E+03	2.66E+03
LQRO037	3	140.87	1.67E+03	4.95E+03	9.43E+03
LQRO043	5	147.97	2.49E+03	7.56E+03	1.45E+04
LQRO044	1	93.59	3.84E+02	9.46E+02	1.73E+03
LQRO049	19	114.20	4.51E+03	1.34E+04	2.53E+04

Name geoth. system	No. of anomalies in system	System´s mean temperature (°C)	System´s thermal energy probability density - Mean and 90% confidence interval (PJ)		
			5%	Mean	95%
LQRO052	2	126.89	6.66E+02	1.96E+03	3.84E+03
LQRO054	1	161.23	5.95E+02	1.61E+03	2.95E+03
LQRO061	1	111.43	4.32E+02	1.29E+03	2.42E+03
LQRO089	9	125.35	9.74E+02	2.99E+03	5.95E+03
LQRO097	3	82.02	7.40E+02	1.85E+03	3.33E+03
LQRO101	1	116.04	4.79E+02	1.37E+03	2.59E+03
LQRO121	2	104.68	8.14E+02	2.32E+03	4.40E+03
LQRO123	1	121.71	4.66E+02	1.43E+03	2.82E+03
LQRO126	1	97.46	3.78E+02	9.99E+02	1.85E+03
LQRO127	3	118.69	1.35E+03	3.99E+03	7.61E+03
LQRO130	3	142.18	1.55E+03	4.65E+03	8.85E+03
LQRO133	1	149.81	5.48E+02	1.66E+03	3.08E+03
LQRO140	3	126.15	1.56E+03	4.52E+03	8.50E+03
LQRO145	1	111.31	4.07E+02	1.15E+03	2.15E+03
LQRO165	1	90.65	3.54E+02	9.96E+02	1.91E+03
LQRO191	1	96.25	3.92E+02	1.16E+03	2.27E+03
LQRO216	2	116.23	5.00E+02	1.58E+03	3.11E+03
LQRO236	1	79.43	3.14E+02	7.44E+02	1.34E+03

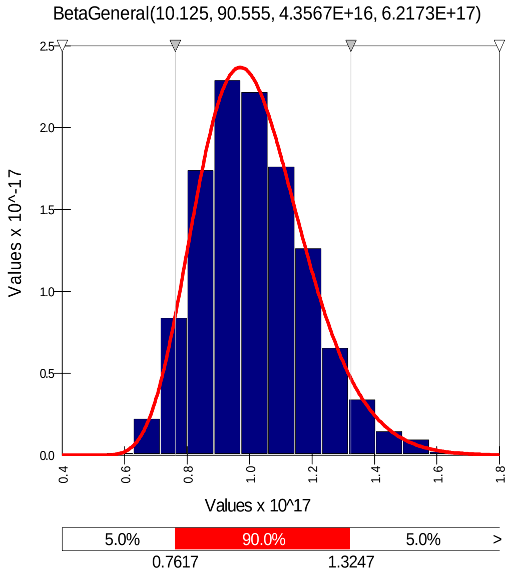

Figure 6: Probability distribution density of the aggregated thermal energy corresponding to the 28 assessed geothermal systems in Queretaro

Applying a recovery factor $R = 0.25$, we estimate the total reserves of the assessed geothermal systems in Queretaro as lying between 1.9×10^4 and 3.3×10^4 PJ, with 90% confidence. The magnitude of these reserves and their associated temperatures are potentially important to positively impact the economic development of the populations co-located with these resources.

These reserves constitute a lower limit to the geothermal reserves of Queretaro. The reasons are that *(a)* the reserves corresponding to 53% of the catalogued geothermal localities could not be estimated for lack of necessary data, and *(b)* that undiscovered resources may exist, for example in regions of the state currently devoid of communications infrastructure (every known geothermal resource in the state lies within short distance of roads or railroads).

CONCLUSIONS

We have estimated the geothermal reserves of 112 (47%) of the known geothermal systems in the Mexican state of Queretaro, and their uncertainties.

We found that the 112 geothermal localities with enough data to estimate reserves are grouped in 28 geothermal systems. We estimated the thermal energy corresponding to these 28 systems, and their 90% confidence intervals. The mean geothermal energy of the assessed individual systems ranges from 6.8 10^2 to 2.8 10^4 PJ. The corresponding most likely areas lie between 2.68 and 46 km^2. And their most likely reservoir temperatures range 77 - 161°C.

We also estimated the aggregated reserves of these 28 systems. They lie between $1.9x10^4$ and $3.3x10^4$ PJ, with 90% confidence. This estimate represents a lower limit to the State's geothermal reserves, because it incorporates only 47% of the known geothermal localities, and there may be more geothermal systems yet undiscovered.

The magnitude of these reserves and their associated temperatures are potentially important to positively impact the economic development of the populations co-located with these resources.

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