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Summary of the 2014 Assessment of Medium- to Low-Temperature Mexican Geothermal Resources

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ABSTRACT

In 2003 we published our first assessment of the medium- to low-temperature (T $\leq$ 200°C) Mexican geothermal resources. It was based on a database of 1,358 geothermal manifestations identified at that time. Due to lack of information on one or more relevant parameters, such as geographical coordinates, reservoir or surface temperature, type of fluid, etc., that assessment included only about 30% of the geothermal manifestations in the database. Since then our group steadily and significantly increased the amount of information in the database by field work and data compilation from different sources, developed a relational database and linked it with a Geographical Information System, and published several partial and complete updates. This work presents a summary of our 2014 assessment of the medium- to low-temperature Mexican geothermal resources based on our current database, which includes 2,376 geothermal manifestations. This assessment incorporates important improvements on the coordinates´ accuracy of a significant number of manifestations, coordinates for manifestations that were lacking before as well as relevant new chemical data. Due to these improvements, the present results include 68.9% of the geothermal manifestations in the database, a vast progress over our first estimate. As before, we relied on the volume method and Montecarlo simulations to estimate geothermal resources and their uncertainties for each identified geothermal system. In all, we estimated the geothermal resources of 927 individual geothermal systems which included 1,637 geothermal manifestations located in 26 of the 32 Mexican States. In most cases these resources would be classified as "inferred resources", according to the Australian Geothermal Code. We then added the inferred thermal energy statistical distributions of the geothermal systems in each State by Montecarlo simulation, to obtain the State´s aggregate geothermal resource. Finally, we added the inferred thermal energy statistical distributions of the geothermal systems in the country, by Montecarlo simulation, and obtained the aggregated resources of the 26 Mexican States and its uncertainty. We also present the statistical distribution of our estimated most likely temperatures in the studied systems. These resources contain massive amounts of thermal energy that could be used in a wide variety of direct applications and power generation. They are potentially important for the economy of 26 of the 32 Mexican States.

1. INTRODUCTION

Due to its particular and complex geologic conditions, Mexico is blessed with abundant geothermal resources. A fair fraction of its high temperature (T > 200°C) catalogued geothermal resources is currently under exploitation in four fields: Cerro Prieto, Los Azufres, Los Humeros and Las Tres Vírgenes. A new field, Cerritos Colorados, is expected to begin power production soon with 75 MWe installed capacity. Several other high-temperature prospects are in different stages of detailed exploration or evaluation. The situation is quite different for medium- to low-temperature geothermal resources. They are seriously underexploited, its main application being balneology. In the current energy scenario information about this abundant resource is important for Mexico.

In 2003 we published our first assessment of the medium- to low-temperature (T $\leq$ 200°C) Mexican geothermal resources (Iglesias and Torres, 2003). It was based on a database of 1,358 geothermal anomalies (surface manifestations, e.g. springs, fumaroles, water wells, etc.) identified at that time. Since then our group significantly increased the amount of information in the database by field work and data compilation from different sources, developed a relational database (Torres *et al.*, 2005) and linked it with a Geographical Information System (Martinez-Estrella *et al.*, 2005). Other publications followed (Iglesias et al., 2005; Iglesias et al., 2009; Iglesias et al., 2010 a; Iglesias et al., 2010 b). This work presents an updated assessment of the medium- to low-temperature Mexican geothermal resources based on our current database which includes 2,376 geothermal manifestations. Figure 1 illustrates the geographical distribution of the 2,082 manifestations with known coordinates.

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

We used the volume method for the present resource assessment. With this method one calculates the thermal energy contained in a given volume of rock and water as (Brook *et al.*, 1978):

$$q_R = \rho_c A h \left(T - T_{ref}\right) \tag{1}$$

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.

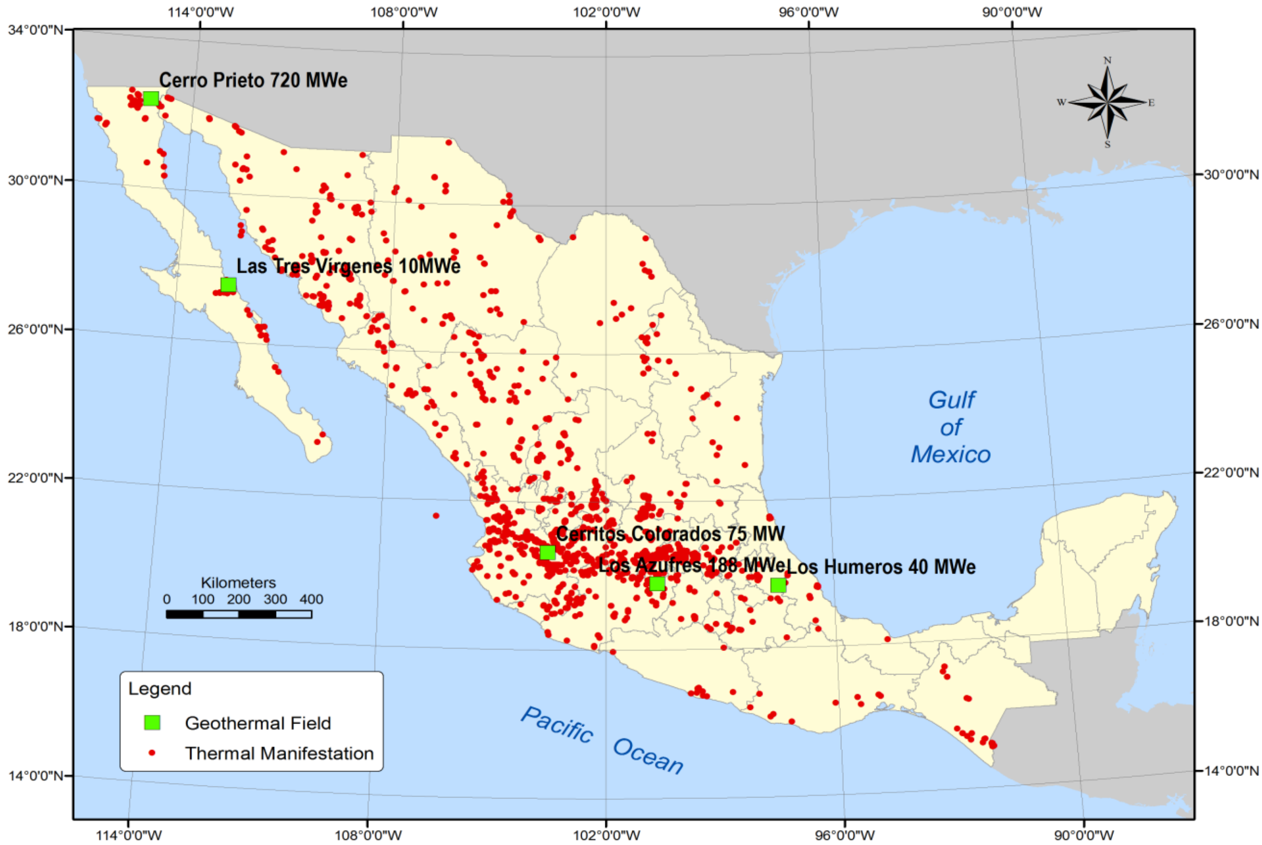

Figure 1: Geographical distribution of the 2,082 manifestations with known coordinates

In order to quantify the uncertainty in the resource assessment, 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.

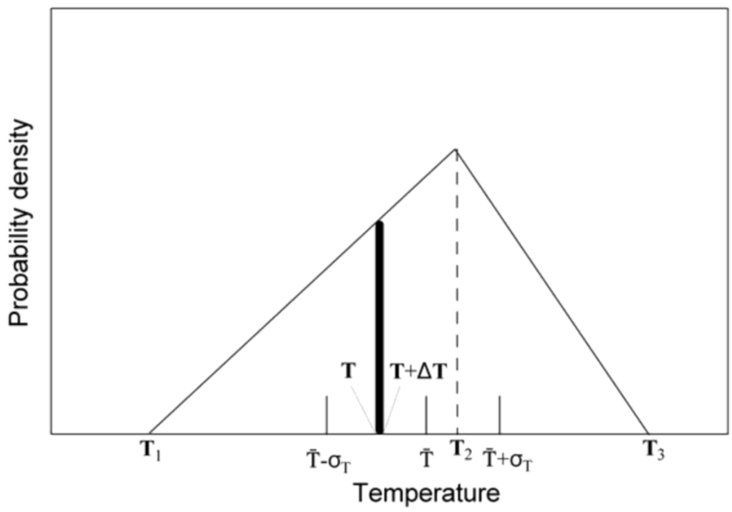

Figure 2: Example of triangular distribution for reservoir temperature

To assess 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 Montecarlo 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.

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 in each State. This problem is analytically intractable (Natheson, 1978). We therefore again used the Monte Carlo method to compute the distribution of total thermal energy in the State. This entailed first fitting analytical probability densities to the computed distributions of local thermal energy, and then running a Montecarlo 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 in each State.

Finally, we computed the Montecarlo addition of all the thermal energy distributions corresponding to the geothermal systems in the country for which we had enough data to compute.

Montecarlo 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. 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 (e.g., Armstead and Tester, 1978).

3. DATA FOR RESOURCE ASSESSMENT

We obtained part of the necessary data from a database compiled and implemented in in our GIS (e.g., Torres *et al*., 2005, Martínez-Estrella et al., 2005), by our workgroup. This database contains detailed information on 2,376 identified geothermal manifestations in Mexico, with sample temperatures greater than 28°C. See Torres et al. (2005 and Martínez Estrella et al (2005) regarding the information fields included.

With the exception of the reference temperature and the value adopted for ρ_C (eq. 1), 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, etc.), 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. Note that our estimates of the most likely reservoir temperature are biased towards lower temperatures due to the inclusion of sample temperatures in the average described in *(d)*. We chose this conservative approach in order to prevent possible overoptimistic temperature estimates.

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 corresponding State, taken from the Mexican Instituto Nacional de Estadística, Geografía e Informática web page (INEGI, 2009).

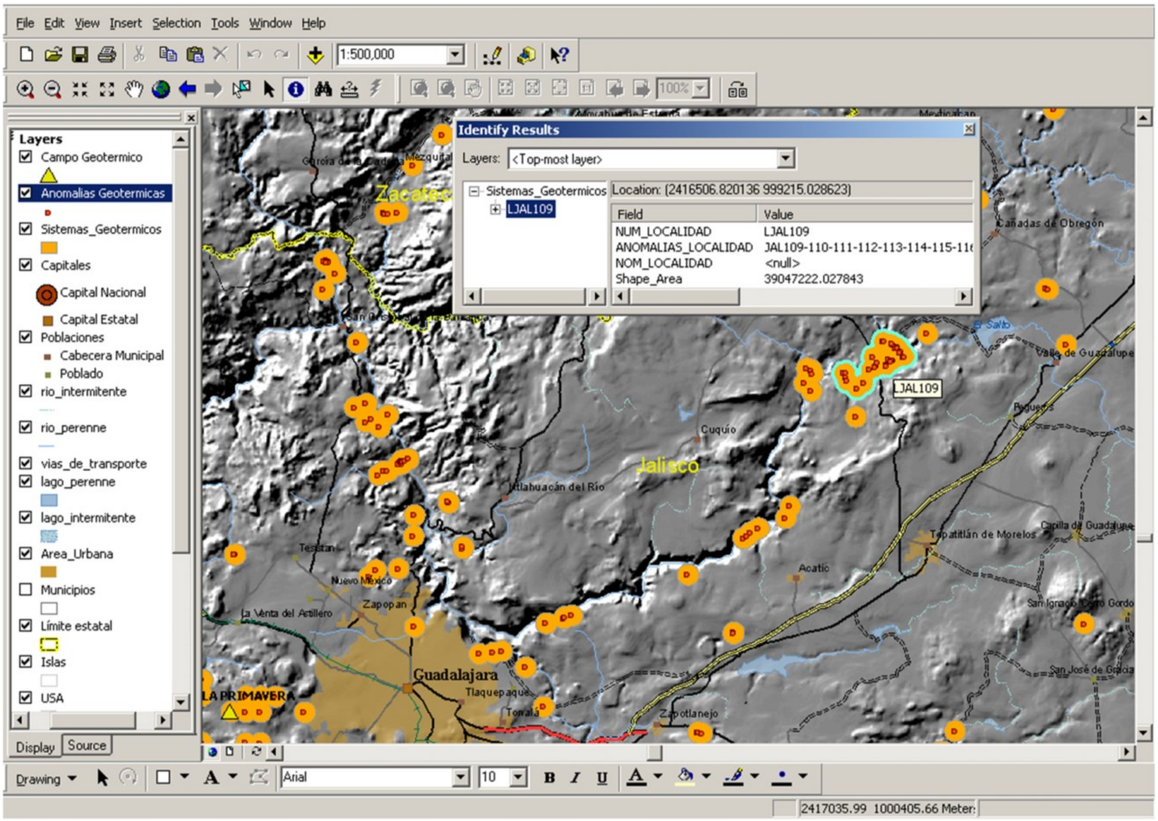

Figure 3: Example of geothermal system´s area (yellow polygons) automatically computed by the SIG, and geothermal manifestations (red points).

4. RESULTS AND DISCUSSION

A significant fraction (31.10%) of the 2,376 geothermal manifestations in our current database lack data on one or more parameters (e.g., geographical coordinates, sample temperature, not enough geothermometers) necessary to estimate the corresponding geothermal resources according to the rules specified in the previous section. Thus we ended up with 1,637 geothermal manifestations to estimate the medium- to low-temperature geothermal resources of the country. In most cases these resources would be classified as "inferred resources", according to the Australian Geothermal Reporting Code (2010).

Using the criteria of the previous section we found that these 1,637 geothermal manifestations are grouped in 927 geothermal systems, located in 26 of the 32 Mexican States. For each of these 927 systems our Montecarlo simulations generated probability density distributions of the estimated reservoir thermal energy, and the statistical parameters mentioned in previous sections. As an example of these results, Fig. 4 presents the distribution corresponding to system LGTO020, which includes 13 geothermal manifestations.

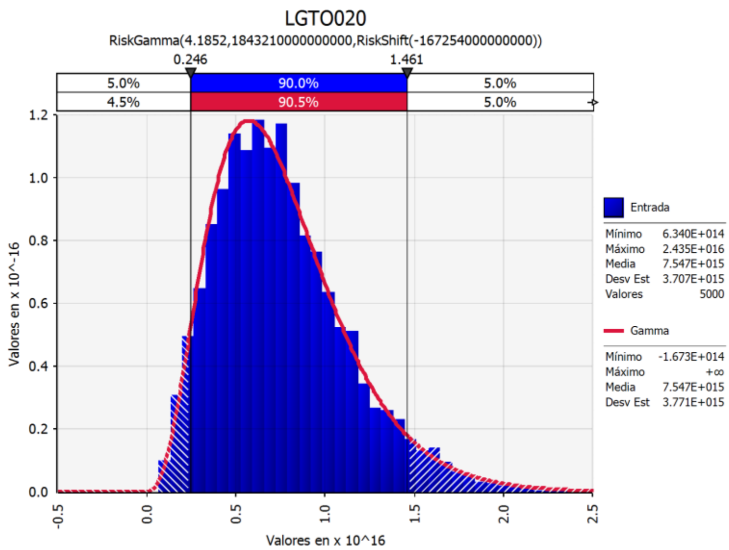

Figure 4: Example of thermal energy probability density for geothermal system LGTO020 (energy in kJ)

Table 1 summarizes our results for the the probability density of total thermal energy corresponding to all the systems in each State. The corresponding most likely areas lie between 2.68 and 46 km^2. The conservatively estimated most likely reservoir temperatures range from 36 to 208 °C. These temperatures are potentially useful for a variety of applications within the socioeconomic environment of the country, 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.

Over the last several years our group received a number of expressions of interest about where to site agricultural, industrial and power-generation applications of geothermal heat. This is a positive change revealing new awareness in Mexican investors about opportunities offered by the country´s geothermal resources.

Table 1: Summary of estimated thermal energy by State

State	# of systems	# of manifesta-tions	Thermal energy and 90% interval (EJ)		
			5%	Mean	95%
Aguascalientes	16	50	41.464	54.499	69.215
Baja California	23	57	30.868	37.68	45.373
Baja California S.	28	37	26.798	31.673	37.09
Chiapas	15	26	19.388	26.597	34.925
Chihuahua	28	58	29.127	33.379	36.273
Cohauila	12	17	12.034	15.27	18.912
Colima	3	4	1.662	2.981	4.576
Durango	47	54	34.119	37.955	42.117
Edo. de Mexico	9	18	10.602	14.102	18.033
Guanajuato	89	146	123.918	136.821	150.459
Guerrero	10	10	4.585	5.908	7.51
Hidalgo	37	87	76.122	92.994	112.24
Jalisco	175	355	253.373	277.243	302.779
Michoacan	69	135	93.662	104.997	116.861
Morelos	6	10	5.48	8.17	11.353
Nayarit	69	134	101.729	116.274	132.37
Nuevo Leon	8	8	6.292	8.788	11.437
Oaxaca	11	12	6.615	8.442	10.445
Puebla	13	17	13.646	17.483	21.722
Queretaro	32	102	91.356	118.11	151.155
San Luis Potosi	25	45	27.438	33.442	39.908
Sonora	128	154	99.352	106.159	113.351
Tamaulipas	8	8	6.305	8.803	11.603
Tlaxcala	3	3	2.144	3.481	5.084
Veracruz	14	15	8.618	10.837	13.375
Zacatecas	49	76	62.366	72.042	83.079
TOTAL	**927**	**1,637**			

As mentioned, we also estimated the probability distribution of the aggregated thermal energy corresponding to the 927 systems by means of a Montecarlo simulation, from the thermal energy distributions of the individual systems. These results are shown in Fig. 5. With the resulting statistical distribution we estimated that the total thermal energy stored in the 927 geothermal systems lies between 1,278 EJ and 1,514 EJ with 90% confidence. The main statistics of this distribution are: mean = 1,383 EJ, mode = 1,374 EJ, median = 1,382 EJ, standard deviation = 33.51 EJ, skewness = 0.1625.

These resources constitute a lower limit to the medium- to low-temperature inferred geothermal resources of Mexico. The reasons are that *(a)* the resources corresponding to 31.10% of the catalogued geothermal manifestations could not be estimated for lack of necessary data, and *(b)* that undiscovered resources may exist.

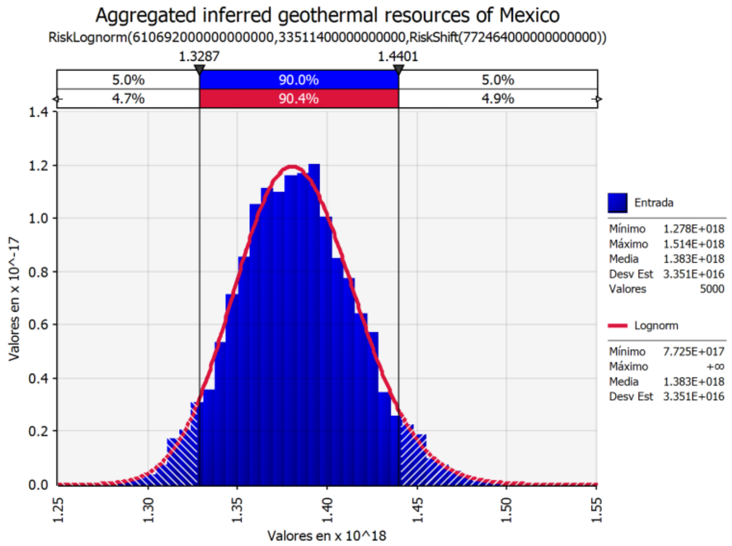

Figure 5: Probability distribution of the aggregated thermal energy (in kJ) corresponding to the 927 assessed geothermal systems.

In Fig. 6 we present the distribution of our estimated most likely reservoir temperatures in the assessed 927 geothermal systems. They span the range 36 – 208 °C. According to Fig. 6, 5% of these systems have temperatures between 149 and 208 °C, 40% of these systems have temperatures between 100 and 149 °C, 50% of these systems have temperatures between 62 and 100 °C and 5% of these systems have temperatures between 36 and 62 °C.

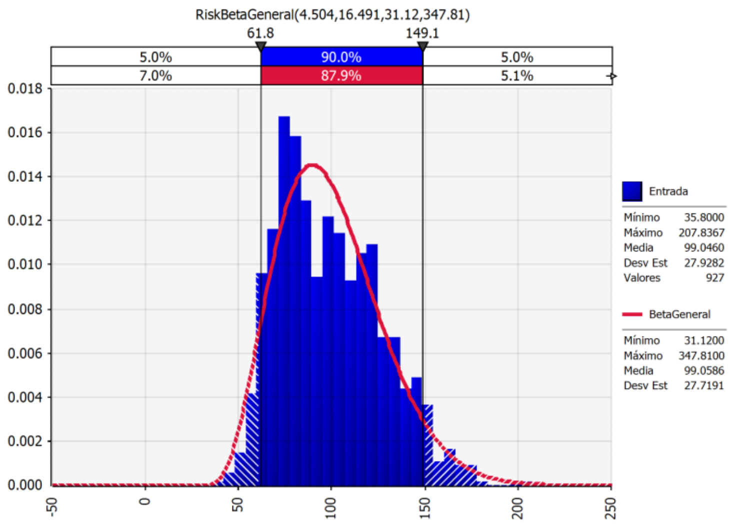

Figure 6: Distribution of our estimated likely reservoir temperature in the assessed 927 geothermal systems.

As mentioned, this assessment incorporates important improvements on the coordinates´ accuracy of a significant number of manifestations, coordinates for manifestations that were lacking before as well as relevant new chemical data, with respect to our 2010 assessment. (Iglesias et al., 2010 a) The main consequences of these improvements were (Fig. 5): an increase of the total number of geothermal systems from 918 to 927; the country´s aggregated mean thermal energy grew from 1,219 EJ to 1,383 EJ (+13.45%); the standard deviation increased 3.65%. The mean most likely reservoir temperature (Fig. 6) changed negligibly (+0.08%).

Focusing on the States (Table 1), the consequences were as follows. *Aguascalientes*: its mean total thermal energy increased 91.75%, due mainly to greater areas of two of the more extensive geothermal localities as a consequence of improved coordinates on some geothermal manifestations. *Baja California*: The number of geothermal manifestations in this State grew from 17 to 23 due to new information on coordinates as well as on chemical data; this resulted in a great increment in the State´s mean total thermal energy of 831.75%. *Chihuahua*: The number of geothermal systems in this state increased from 24 to 28, and its mean total thermal energy increased by 11.49%. *Baja California Sur, Chiapas, Guanajuato*, and *Hidalgo* experienced negligible changes of their mean total thermal energies. The rest of the states remained as in our 2010 assessment.

5. CONCLUSIONS

We have estimated the inferred geothermal resources of 927 (69%) of the currently identified medium- to low-temperature geothermal systems in Mexico, and their uncertainties.

We found that the 1,637 geothermal manifestations with enough data to estimate inferred resources are grouped in 927 geothermal systems located in 26 of the 32 Mexican States. We estimated the thermal energy corresponding to these 927 systems, and their 90% confidence intervals. The mean thermal energy of the assessed individual systems ranges from 2.98 to 277.24 EJ. The corresponding most likely areas lie between 2.68 and 46 km^2. With these results we estimated the aggregated inferred resources of each of the 26 States and their corresponding uncertainties.

We also estimated the aggregated inferred resources of the 927 geothermal systems. They lie between 1,278 EJ and 1,514 EJ with 90% confidence. This estimate represents a lower limit to Mexico's inferred geothermal resources of medium- to low-temperature, because it incorporates only 69% of the identified geothermal manifestations, and there may be more geothermal systems yet undiscovered.

Our estimated most likely reservoir temperatures in the assessed 918 systems span the range 36 – 208 °C. Five percent of these systems have temperatures between 149 and 208 °C, 40% of these systems have temperatures between 100 and 149 °C, 50% of these systems have temperatures between 62 and 100 °C and 5% of these systems have temperatures between 36 and 62 °C.

The new data incorporated in our database since 2010 resulted in an increase of the total number of geothermal systems from 918 to 927; the country´s aggregated mean thermal energy grew from 1,219 EJ to 1,383 EJ (+13.45%); and its standard deviation increased 3.65%. The mean most likely reservoir temperature (Fig. 6) changed negligibly (+0.08%). The mean total thermal energy increased by 91.75% for Aguascalientes, by 831.75% for Baja California and by 11.49% for Chihuahua. Essentially no other changes were experienced by the rest of the States.

The magnitude of these inferred resources and their associated temperatures are potentially important to positively impact the economic development of the country. Over the last several years our group received a number of expressions of interest about where to site agricultural, industrial and power-generation applications of geothermal heat. This is a positive change revealing new awareness in Mexican investors about opportunities offered by the country´s geothermal resources.

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