Summary of the 2010 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 ≤ 200°C) Mexican geothermal resources. It was based on a database of 1,358 geothermal manifestations (surface manifestations, e.g. springs, fumaroles, water wells, etc.) 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 significantly increased the amount of information in the database by field work and data compilation from different sources, and then developed a relational database and linked it with a Geographical Information System. This work presents an updated assessment of the medium- to low-temperature Mexican geothermal resources based on our current database which includes 2,361 geothermal manifestations. As before, we relied on the volume method and Montecarlo simulations to estimate geothermal resources and their uncertainties for each identified geothermal system. These geothermal systems very often include more than one geothermal manifestation, generally increasing the reliability of the individual estimations. In all, we estimated the geothermal resources of 918 individual geothermal systems which included 1,797 geothermal manifestations (as before, a significant fraction of the identified manifestations lack relevant information) 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 922 geothermal systems by Montecarlo simulation, to obtain the total estimable geothermal resources of the 26 Mexican States and its uncertainty. With the resulting statistical distribution we estimated that the total thermal energy stored in the 922 geothermal systems lies between 1,168 EJ and 1,274 EJ with 90% confidence. The statistical distribution of the (conservatively) inferred reservoir temperatures indicates that 5% of these systems have temperatures between 151 and 208 °C, 40% of these systems have temperatures between 102 and 151 °C, 50% of these systems have temperatures between 60 and 102 °C and 5% of these systems have temperatures between 36 and 60 °C. 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.

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.

Figure 1. Geographical distribution of identified geothermal manifestations in Mexico.

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, and then developed a relational database (Torres *et al*., 2005) and linked it with a Geographical Information System (Martinez-Estrella *et al*., 2005). This work presents an updated assessment of the medium- to low-temperature Mexican geothermal resources based on our current database which includes 2,361 geothermal manifestations. Figure 1 illustrates their geographical distribution.

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.

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):

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

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 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.

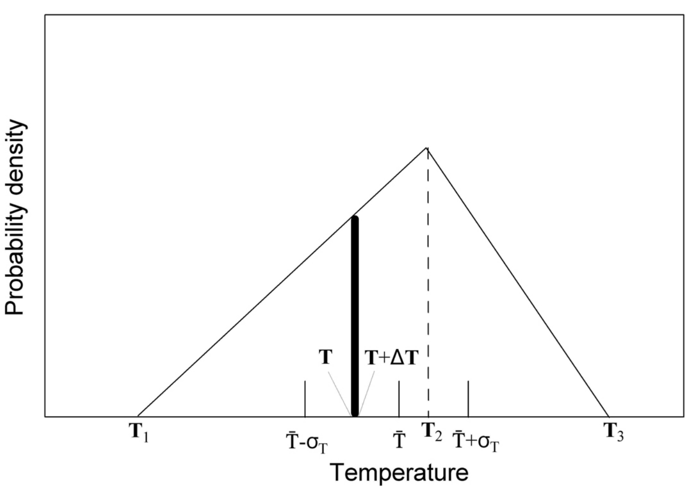

Figure 2. Example of triangular distribution for reservoir temperature.

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* (Figure 2). The parameters in Figure 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: higher numbers of iterations (we tried 500 to 10,000) resulted in minimal changes in the results.

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).

Data for Resource 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 2,361 identified geothermal manifestations in Mexico, with sample temperatures greater than 28°C. The available information includes, for many geothermal manifestations, 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.

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.

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., Figure 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).

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.

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).

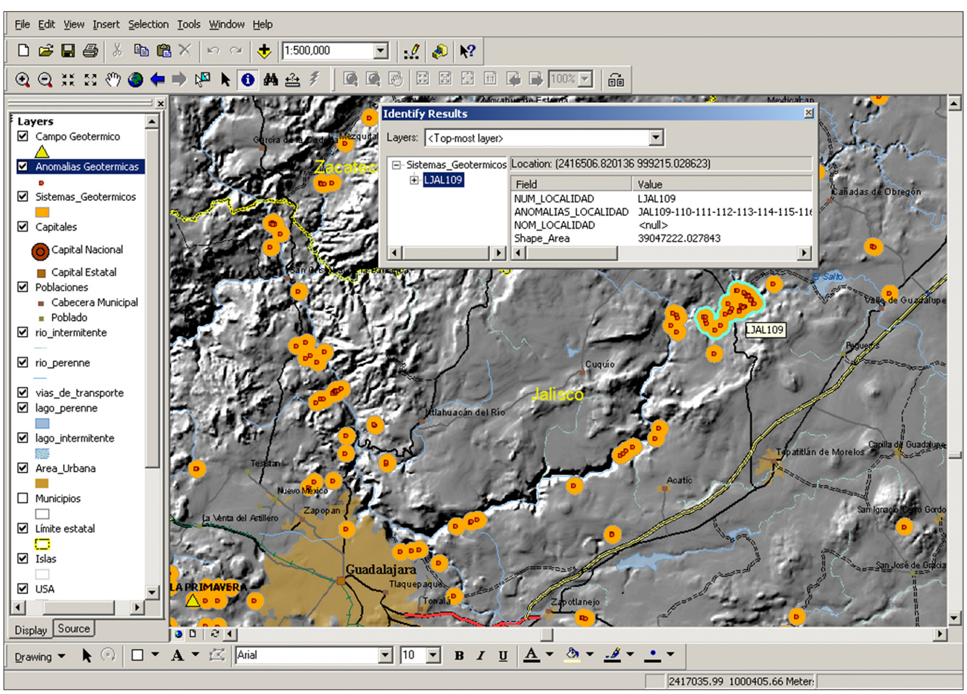

Figure 3. Example of geothermal system´s area (yellow polygons) automatically computed by the SIG, and geothermal manifestations (red points).

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).

Results and Discussion

A significant fraction (23.89%) of the 2,361 geothermal manifestations in our 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 1,797 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 Code.

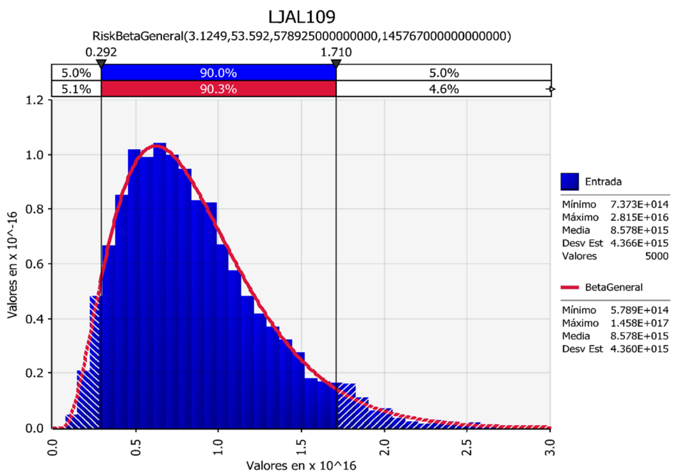

Figure 4. Example of thermal energy probability density for geothermal system LJAL109 (energy in kJ).

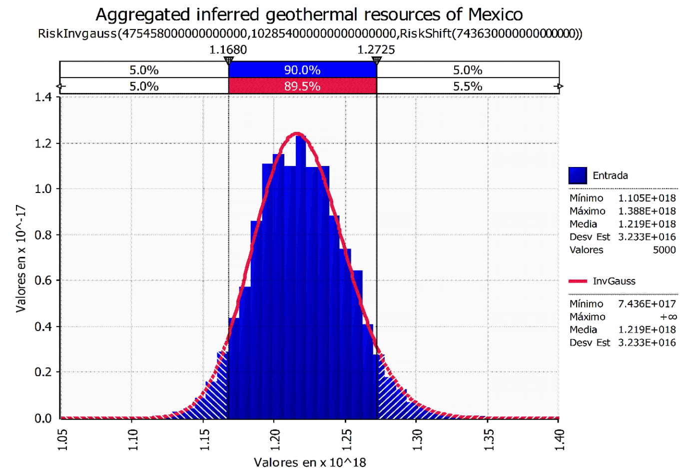

Figure 5. Probability distribution of the aggregated thermal energy (in kJ) corresponding to the 918 assessed geothermal systems.

Using the criteria of the previous section we found that these 1,797 geothermal manifestations are grouped in 918 geothermal systems, located in 26 of the 32 Mexican States. For each of these 918 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, Figure 4 presents the distribution corresponding to system LJAL109, which includes 36 geothermal manifestations.

Table 1 summarizes our results for the the probability density of total thermal energy corresponding to all the systems in each

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	49	22.111	28.422	35.618
Baja California	17	47	2.757	4.044	5.517
Baja California S.	28	38	26.720	31.590	36.883
Chiapas	15	26	19.457	26.093	34.046
Chihuahua	24	56	25.861	29.938	34.420
Cohauila	12	17	12.034	15.270	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	123.112	135.806	149.202
Guerrero	10	10	4.585	5.908	7.510
Hidalgo	37	93	75.652	92.359	111.437
Jalisco	175	355	253.373	277.243	302.779
Michoacan	69	135	93.662	104.997	116.861
Morelos	6	10	5.480	8.170	11.353
Nayarit	69	134	100.865	115.551	131.387
Nuevo Leon	8	8	6.292	8.788	11.437
Oaxaca	11	12	6.615	8.442	10.445
Puebla	14	16	18.017	23.838	18.017
Queretaro	32	102	91.356	118.110	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	**918**	**1,631**			

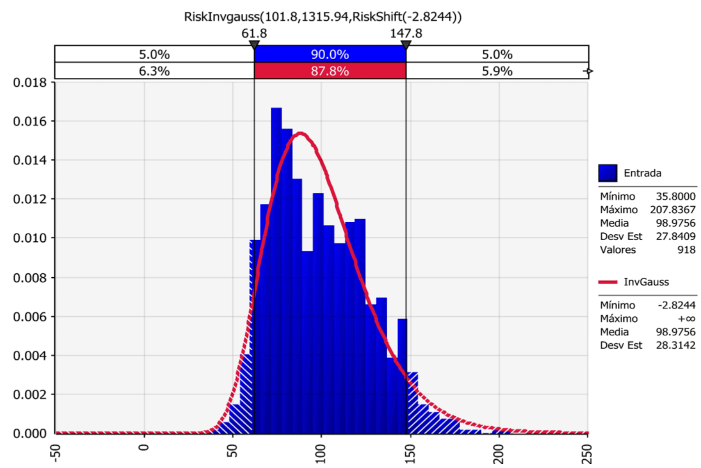

Figure 6. Distribution of our estimated most likely reservoir temperatures in the assessed 918 geothermal systems.

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 two years our group received several 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.

As mentioned, we also estimated the probability distribution of the aggregated thermal energy corresponding to the 918 systems by means of a Montecarlo simulation, from the thermal energy distributions of the individual systems. These results are shown in Figure 5. With the resulting statistical distribution we estimated that the total thermal energy stored in the 918 geothermal systems lies between 1,168 EJ and 1,274 EJ with 90% confidence. The main statistics of this distribution are: mean = 1,219 EJ, mode = 1,215 EJ, median = 1.218 EJ, standard deviation = 32.33 EJ, skewness = 0.2137.

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 23.89% of the catalogued geothermal manifestations could not be estimated for lack of necessary data, and *(b)* that undiscovered resources may exist.

In Figure 6 we present the distribution of our estimated most likely reservoir temperatures in the assessed 918 geothermal systems. They span the range 36 – 208 °C. According to Figure 6, 5% of these systems have temperatures between 151 and 208 °C, 40% of these systems have temperatures between 102 and 151 °C, 50% of these systems have temperatures between 60 and 102 °C and 5% of these systems have temperatures between 36 and 60 °C.

Conclusions

We have estimated the inferred geothermal resources of 918 (76%) of the known medium- to low-temperature geothermal systems in Mexico, and their uncertainties.

We found that the 1,797 geothermal manifestations with enough data to estimate inferred resources are grouped in 918 geothermal systems located in 26 of the 32 Mexican States. We estimated the thermal energy corresponding to these 918 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. This is reported in Table 1.

We also estimated the aggregated inferred resources of the 918 geothermal systems. They lie between 1,168 EJ and 1,274 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 76% of the known 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 151 and 208 °C, 40% of these systems have temperatures between 102 and 151 °C, 50% of these systems have temperatures between 60 and 102 °C and 5% of these systems have temperatures between 36 and 60 °C.

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 two years our group received several 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.

References

Armstead, H.C.H. and Tester, J.W., *Heat Mining*, E. & F.N. Spon Ltd, London (1978).

Brook, C.A., Mariner R.H., Mabey D.R., Swanson J.R., Guffanti M., and Muffler L.J.P.: Hydrothermal Convection Systems with Reservoir Temperatures ≥ 90°C. In: Muffler L.P.J., Assessment of Geothermal Resources of the United States – 1978, Circular 790, U.S. Geological Survey, pp. 18-85 (1978).

Grant, M.A., Donaldson, I.G. and Bixley, P.F., *Geothermal Reservoir Engineering. Chapter 3: Simple quantitative models*. Academic Press pp. 46-75 (1982).

Iglesias, E.R. and Torres, R.J.: Low- to medium-temperature geothermal reserves in Mexico: a first assessment, *Geothermics*, vol. 43, pp. 711-719 (2003).

INEGI (Instituto Nacional de Estadística, Geografía e Informática), México, *web page* http://mapserver.inegi.gob.mx/geografía/espanol/estados/ags/temper-tot-mens.cfm (2009).

Martínez-Estrella, I., Torres, R.J. and Iglesias, E.R., A GIS-based information system for moderate-to low-temperature Mexican geothermal resources, *Proceedings World Geothermal Congress 2005*, paper 1725, 8 pp. (2005).

Natheson, M., Methodology of determining the uncertainty in accesible geothermal resource base of identified hydrothermal convection systems, *US Geological Survey Open-File Report* 78-1003, p. 50 (1978).

Torres, R.J., Martínez-Estrella, J.I. and Iglesias E.R., Database of Mexican medium- to low-temperature geothermal resources. *Proceedings World Geothermal Congress 2005*, paper 1724, 4 pp. (2005).