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Medium- to Low-Temperature Geothermal Reserves of the State of Aguascalientes, Mexico: a Partial Assessment

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ABSTRACT

As we have shown in previous work, Mexico is blessed with important medium- to low-temperature (T<200°C) geothermal reserves, which are currently grossly underutilized. Our previous work focused on the aggregated geothermal reserves of all the Mexican states with known geothermal resources. In this paper we present a partial assessment of the geothermal reserves of the state of Aguascalientes. This assessment is partial of necessity, due to the current lack of information necessary to cover all the geothermal resources of this state.

Our assessment includes 81.25% of the identified geothermal surface anomalies, distributed in 14 geothermal localities, with surface areas ranging between 2.6 and 16 km^2. We used the volume method, complemented with Monte Carlo simulations, and a recovery factor equal to 25%, to estimate geothermal reserves and their inherent uncertainties. Our results indicate that the aggregated reserves of these 14 geothermal localities lie between 0.68x10^{16} and 1.21x10^{16} kJ, with 90% confidence. The most likely reservoir temperatures lie between 55 and 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; greenhouse heating; fish farming; and spas. 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.

1. INTRODUCTION

Our group has been involved in assessing the medium- to low-temperature geothermal reserves of Mexico for the last few years. Recently we published a first report (Iglesias and Torres, 2003) that included our reserve estimates for 276 geothermal localities spread over 20 Mexican states. Due to space limitations, our report presented only the aggregated results for these localities, but we intend disseminating our results on a state-by-state basis. In this paper we address the geothermal reserves of the Mexican State of Aguascalientes (Spanish for "hot waters").

Since the publication of the report mentioned above, we have significantly updated our database (e.g., Torres *et al.* 2005). The present assessment includes the new data.

The state of Aguascalientes is located in the geographic center of Mexico, and covers an area of 5,589 km^2. Three different geologic provinces converge on its territory (Fig. 1). The Sierra Madre Occidental occupies nearly the whole western half of the state; the Mesa Central covers most of the eastern part of the state; and the Trans-Mexican Volcanic Belt overlays a small part of its southern territory (Fig. 1). Aguascalientes has abundant geothermal resources. In fact, the name of its capital city, and by extension that of the state, derives from the existence of numerous hot springs in the city area and its environs, at the time of the city's foundation.

Our database catalogs 64 domestic water wells, which produce fluids with temperatures in the 28-52°C range, and at least five thermal water spas in the state. The majority of these resources line up on a central graben dividing the Sierra Madre Occidental from the Mesa Central geologic provinces (Fig. 1). However, this correlation is probably a selection effect, due to the advantages offered by this central valley for human activities, such as agriculture, dairy farming, road and railroad construction, etc. In fact, all the registered geothermal manifestations in our Aguascalientes database lie close to roads and railroads (Fig. 1). This lends support to our hypothesis that a selection effect, due to the existence of nearby communications facilities, significantly affects the location of the registered geothermal anomalies.

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 current 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.

To determine the uncertainty in these estimates we assume, for each variable, a triangular probability density that represents our subjective judgment of the true density. As an example, let’s take the variable reservoir temperature (Fig. 2). The parameters in Fig. 1 are defined as: T_1 = minimum reservoir temperature; T_2 = most likely reservoir temperature; T_3 = maximum reservoir temperature. The mean ! 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 $T + \Delta T$.

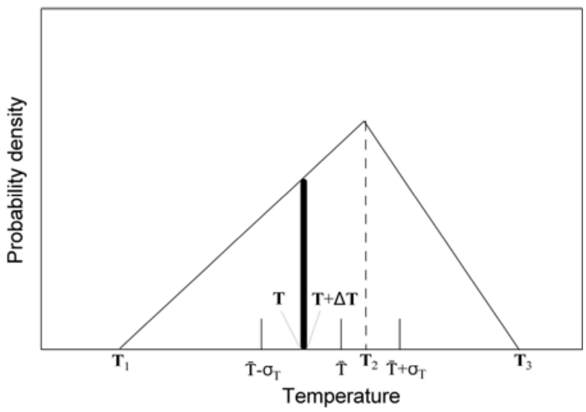

Figure 2: Example of triangular distribution for reservoir temperatures.

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.

Using the Monte Carlo method to compute the thermal energy of individual localities 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 distributions of thermal energy for the individual systems included in this assessment, we calculated, from them, the distribution 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 14 computed distributions of local thermal energy, and then running a Monte Carlo simulation with them. Having obtained this distribution we are 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.

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 manifestations in Mexico, with sample temperatures greater than 28°C. The available information includes, for each geothermal manifestation, 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 64 geothermal manifestations in Aguascalientes. All of them are water wells. This is not surprising because the state is predominantly arid.

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, 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 manifestations overlap (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 a 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 Aguascalientes, taken from the Mexican Instituto Nacional de Estadística, Geografía e Informática (INEGI, 2004) web page.

4. RESULTS AND DISCUSSION

Using the criteria of the previous section we found that the 64 known geothermal manifestations are grouped in 17 geothermal systems (Fig. 3). The corresponding most likely areas lie between 2.68 and 16 km^2.

Of these systems, 14 have enough data to estimate the corresponding reserves. At present the data required to estimate the geothermal reserves corresponding to systems LAGS006, LAGS012 and LAGS018 are lacking. We were therefore able to estimate the geothermal reserves of 83% of the systems.

The most likely reservoir temperatures range from 55 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; greenhouse heating; fish farming; and spas.

For each of these 14 systems our Monte Carlo simulations generated probability 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 LAGS038, which includes 15 wells.

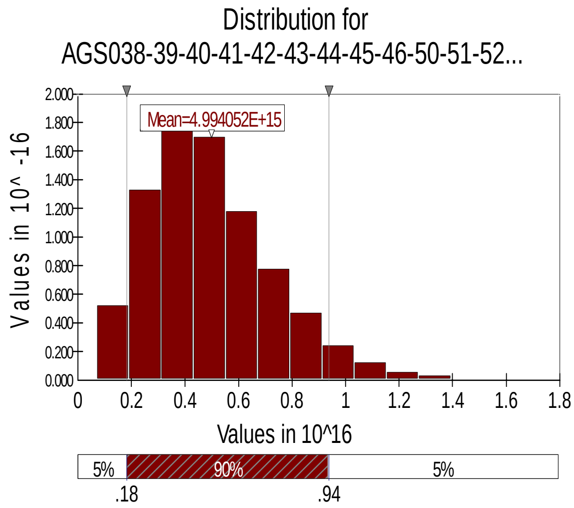

Figure 4: Probability distribution of reservoir thermal energy (in kJ) for the geothermal system LAGS038. Note the 90% confidence interval and the distribution mean.

Table 1: Summary of results for individual systems

System	# of wells	Distribution mean (in kJ x 10^{15})	90% confidence interval (in kJ x 10^{15})
LAGS001	6	3.85	1.46 – 6.98
LAGS016	13	10.11	3.58 – 18.45
LAGS020	1	0.62	0.29 – 1.06
LAGS021	1	1.44	0.52 – 2.73
LAGS025	2	1.51	0.54 – 2.83
LAGS030	3	4.16	1.52 – 7.70
LAGS035	4	2.84	1.17 – 4.99
LAGS038	15	4.99	1.82 – 9.38
LAGS047	1	1.61	0.51 – 3.15
LAGS048	1	1.59	0.64 – 2.89
LAGS056	1	0.67	0.25 – 1.22
LAGS059	1	1.48	0.46 – 2.82
LAGS061	2	1.54	0.54 – 2.85
LAGS063	1	0.47	0.19 – 0.86

There is a correlation between the number of wells included in the system and the mean of the corresponding distribution of thermal energy, as illustrated in Fig. 5. In principle one should expect it, because more wells in the system tend to increase its area, and that increases the system's energy (equation 1). However, increasing the number of wells does not always increase its area. For example, the area of system LAGS038 (15 wells) is significantly smaller than that of LAGS016 (13 wells), as shown in Fig. 3. Deviations about the correlation line of Fig. 5 are of course also due to differences in reservoir temperature, and reservoir thickness.

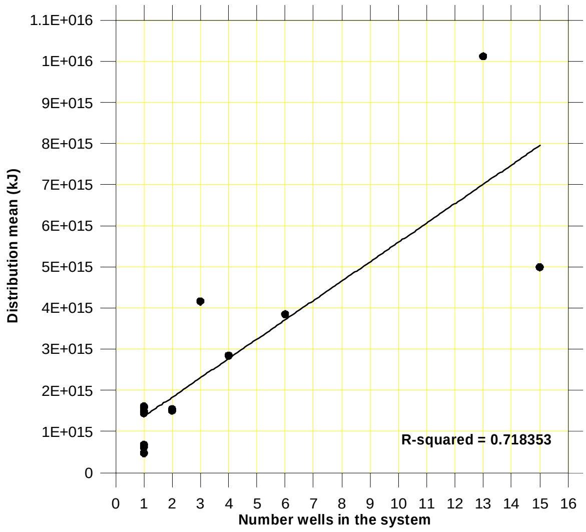

Figure 5: Correlation between the number of wells in the system and its thermal energy distribution mean.

As mentioned in section 2, we estimated the probability distribution of the total thermal energy corresponding to the 14 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 2.73 10^{16} and 4.82 10^{16} kJ (7.58 10^{9} and 1.338 10^{10} MWh), with 90% confidence. The main statistics of this distribution are: mean = 3.70 10^{16} kJ, mode = 3.56 10^{16} kJ, median = 3.65 10^{16} kJ, standard deviation = 6.37 10^{15} kJ, skewness = 0.4353.

Applying a recovery factor R = 0.25, we estimate the total reserves of the assessed geothermal systems in Aguascalientes as lying between 0.68 10^{16} and 1.21 10^{16} kJ (1.89 10^{9} and 3.35 10^{9} MWh), 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 probably constitute a lower limit to the geothermal reserves of Aguascalientes. We surmise this considering that *(a)* the reserves of the known systems LAGS006, LAGS012 and LAGS018 could not be estimated 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).

5. CONCLUSIONS

We have estimated the geothermal reserves of 83% of the known geothermal systems in the Mexican state of Aguascalientes, and their uncertainties. The total estimated reserves lie between 0.68 10^{16} and 1.21 10^{16} kJ (1.89 10^{9} and 3.35 10^{9} MWh), with 90% confidence.

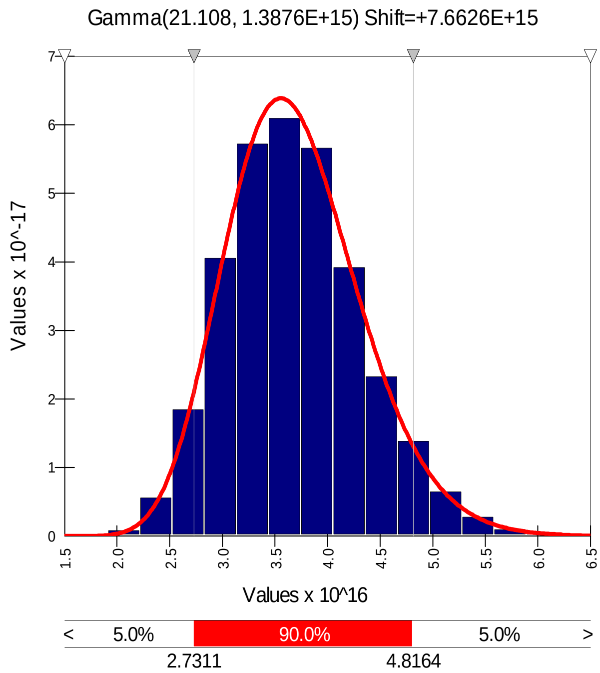

Figure 6: Probability distribution of the total thermal energy corresponding to the 14 assessed geothermal systems in Aguascalientes

We found that the 64 known geothermal manifestations are grouped in 17 geothermal systems. We were able to estimate the thermal energy corresponding to 14 of these systems, and their 90% confidence intervals. The mean geothermal energy of the assessed systems ranges from 6.20 10^{14} to 1.01 10^{16} kJ. The corresponding most likely areas lie between 2.68 and 16 km^2. And their most likely reservoir temperatures are between 55 and 161°C.

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.

REFERENCES

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

Bodvarsson, G., Geothermal resource energetics, *Geothermics*, vol. 3, pp. 83-92 (1974).

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 (2004).

Martínez-Estrella, I., Torres, R.J. and Iglesias, E.R., A GIS-based information system for moderate-to low-temperature Mexican geothermal resources, *These Proceedings* (2005).

Muffler, L.J.P. and Cataldi, R., Methods for regional assessment of geothermal resources, *Geothermics*, vol. 7, pp. 53-89 (1978).

Natheson, M., Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas, *US Geological Survey Open-File Report* 75-525, p. 35 (1975).

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

Natheson, M. and Muffler, L.J.P., Geothermal resources in hydrothermal convection systems and conduction-dominated areas, In: White, D.E., Williams, D.L. (Eds>), *US Geological Survey Circular 726*, pp. 104-121 (1975).

Torres, R.J., Martínez-Estrella, J.I. and Iglesias E.R., Database of Mexican medium- to low-temperature geothermal resources. *These Proceedings* (2005).

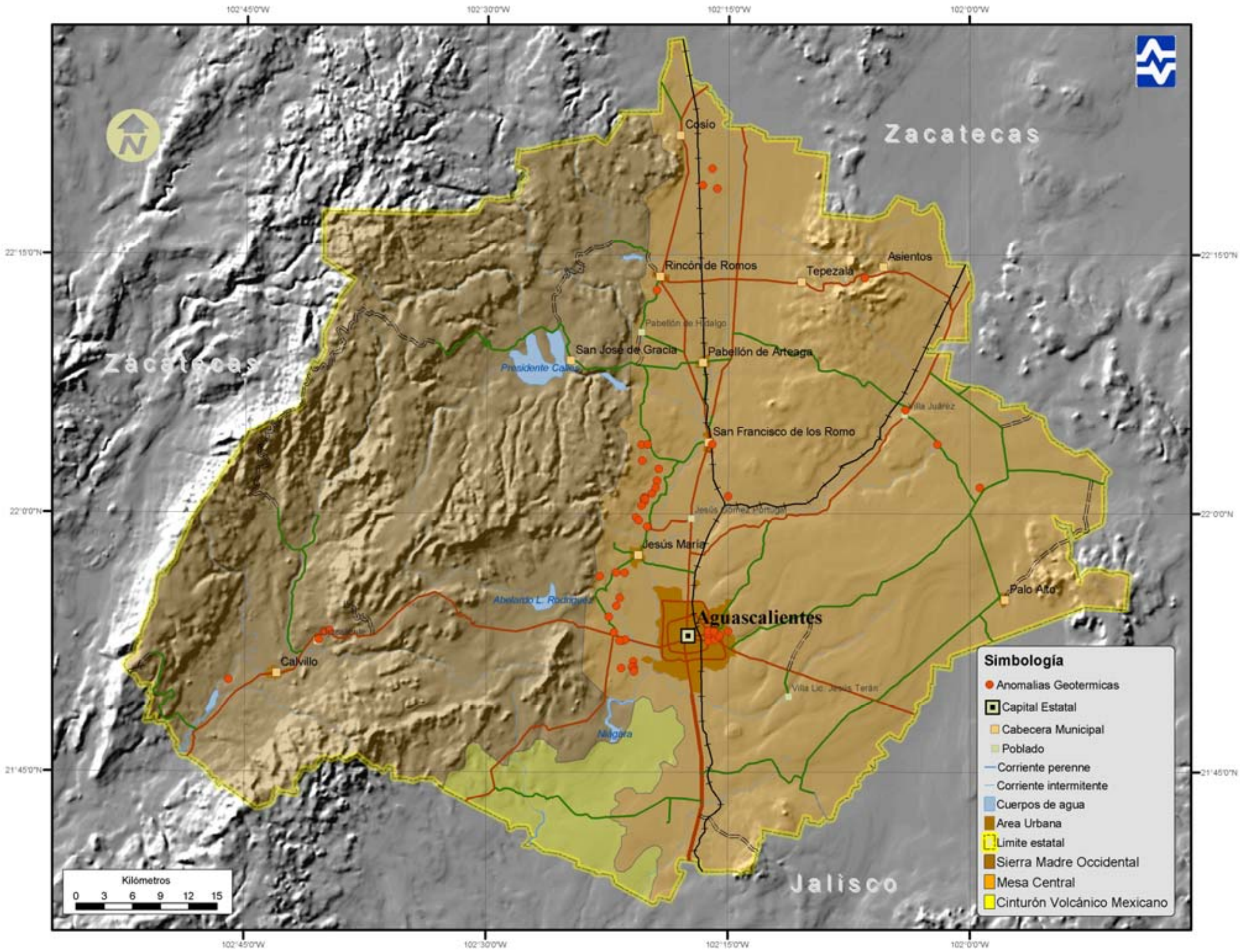

Figure 1:The state of Aguascalientes, showing the three geological provinces that converge on it, and the known geothermal manifestations in it.

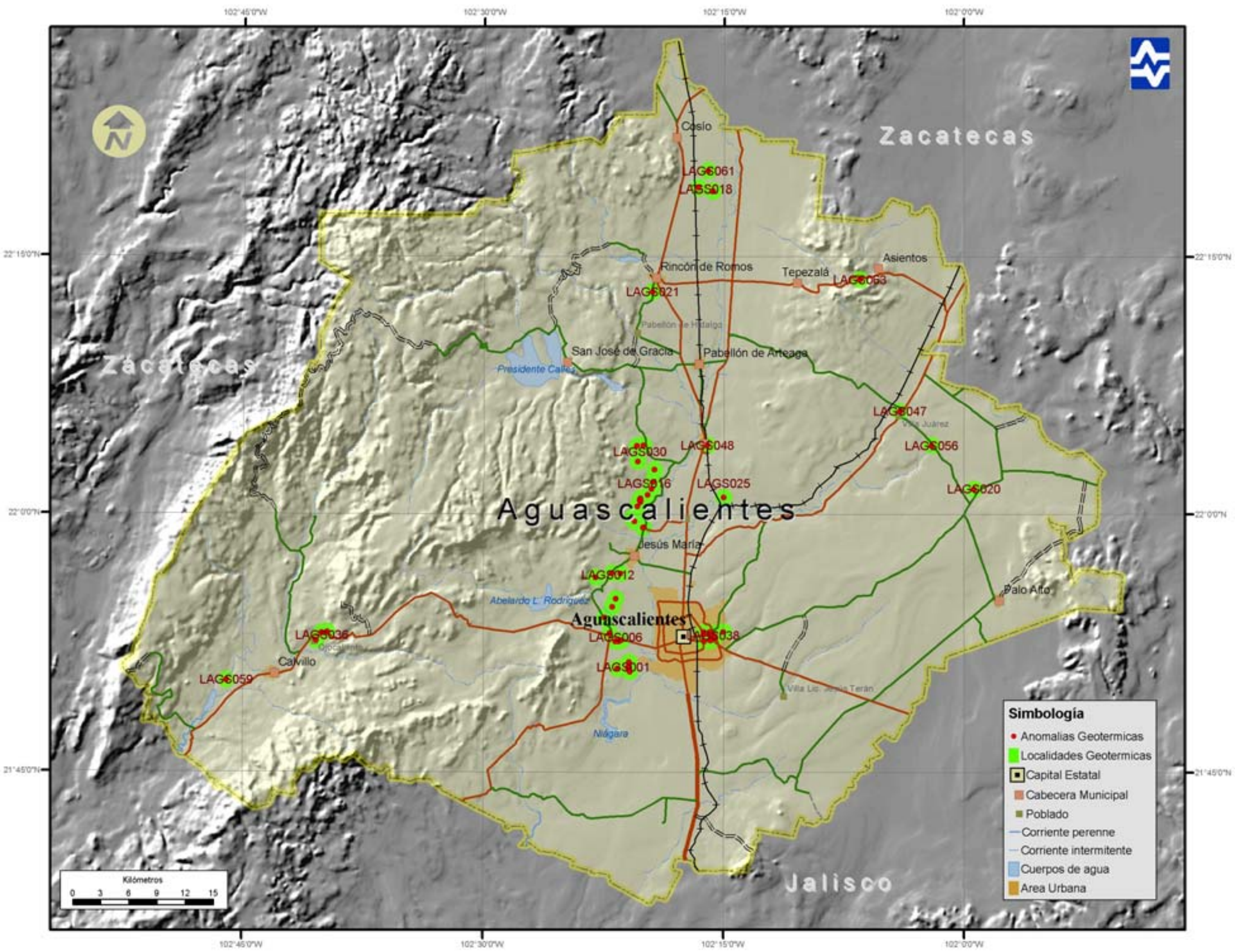

Figure 3: Known geothermal systems in the State of Aguascalientes