PROBABILISTIC ASSESSMENT OF ELECTRICAL POTENTIAL OF TOCOMAR GEOTHERMAL FIELD (CENTRAL PUNA - NW ARGENTINA) USING VOLUMETRIC METHOD.

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ABSTRACT

The geological conditions along the Central Andes of South America allow the formation of geothermal fields of high, medium and low enthalpy. Despite the fact that Argentina has a high geothermal potential, the specific assessment of this resource is actually scarce. In this work, the first preliminary estimate of the geothermal potential of the Tocomar geothermal field for electricity production is presented. All the calculations were carried out using the reformulated USGS heat in place volumetric method, together with Monte Carlo simulations. The reservoir specific parameters required in the formulas were estimated from geological, geochemistry and geophysical data, thus the results are for an inferred geothermal resource. Multiple iterations have been performed modifying the probability distribution of each assumption to produce different forecasts. We analysed the electric generation capacity of the geothermal reservoir with a probabilistic approach due to the uncertainty level of each parameter and the exploration state of the project. The Tocomar geothermal field has a power production capacity between ~6 MWe (P90) to ~56 MWe (P10). The recovery factor, as it is expected, is the most sensitive variable in the estimation of the potential electric power generation and it has a linear correlation with the power output. The strategic geographical position of Tocomar and its geothermal potential for power generation offer a promising scenario for the future development of this field that could largely mitigate local socio-economic problems and provide an energy alternative allowing the exploitation of several mining projects (Li, Cu, Au, Ag) often economically unviable due to the lack of traditional energy resources.

1. INTRODUCTION

Argentina has an estimated geothermal potential of 490 - 2010 MWe (Gawell et al., 1999), but up to date there is no an updated resource assessment neither geothermal energy production. Bona and Coviello (2016) have identified several factors that affect the development of geothermal energy in the region, the most conditioning ones being technical and economic factors. Due to this, investment tends to focus on advanced projects rather than on exploring new areas. Developing new projects (i.e. greenfield) is a high-risk activity with high initial costs and a slow rate of return (IGA 2013), so the integration of preliminary conceptual models and estimates of geothermal potential represent relatively low-cost, high-profit tools. Having quality information is essential for reducing uncertainty and ensuring the progress of a project.

In this paper, we present the first assessment of the potential of the Tocomar geothermal field for electricity production using the USGS “Heat-in-place” volumetric method, as reformulated by Garg and Combs (2015). We also analyze, after multiple iterations, the significance and statistical weight of the variables in the probabilistic calculation, and their interdependence. Furthermore, we discuss and compare the results obtained by modifying the distribution assigned to each variable, and we simulate their responses to different forecasts.

2. GEOLOGICAL FRAMEWORK

The Tocomar Geothermal Field (TGF, 24.185°S - 66.560°W) is located on the central Puna plateau, on the Calama - Olacapato - El Toro (COT) lineament (Fig.1). The COT lineament consists of a system of NW-striking, left-lateral faults and fractures, and of smaller ENE-striking associated structures. Deformation along the COT occurred during and after the activity of the N-S thrusts, and is coeval with the intense magmatism that occurs mainly in the central area of the lineament (Norini et al. 2013). The TGF is located in that section with several geothermal manifestations as travertine deposits, siliceous sinter and hot springs with temperatures up to 75 °C. It is spatially associated with the Tocomar volcanic center (0.55 Ma, Petrinovic et al., 1999), whose pyroclastic deposits overlie igneous and metamorphic rocks of the Ordovician basement, Cretaceous sedimentary rocks of the Pirgua subgroup, Miocene ignimbrites associated with the Aguas Calientes caldera and Pleistocene sediments (Taviani 1997; Petrinovic and Colombo 2006). The current preliminary conceptual model proposed for the Tocomar geothermal system, based on stratigraphic, hydrogeological, geochemical and structural data, together with MT model, consists of a highly-fractured main reservoir located within the Ordovician basement, at a depth of 0.8-1.5 km (Ahumada et al., 2017), a reservoir temperature of 131 ºC – 229 ºC (Giordano et al. 2016) and a heat source associated with the volcanism of the Tocomar Volcanic Center.

3. METHODOLOGY

3.1 USGS “Heat-in-Place”

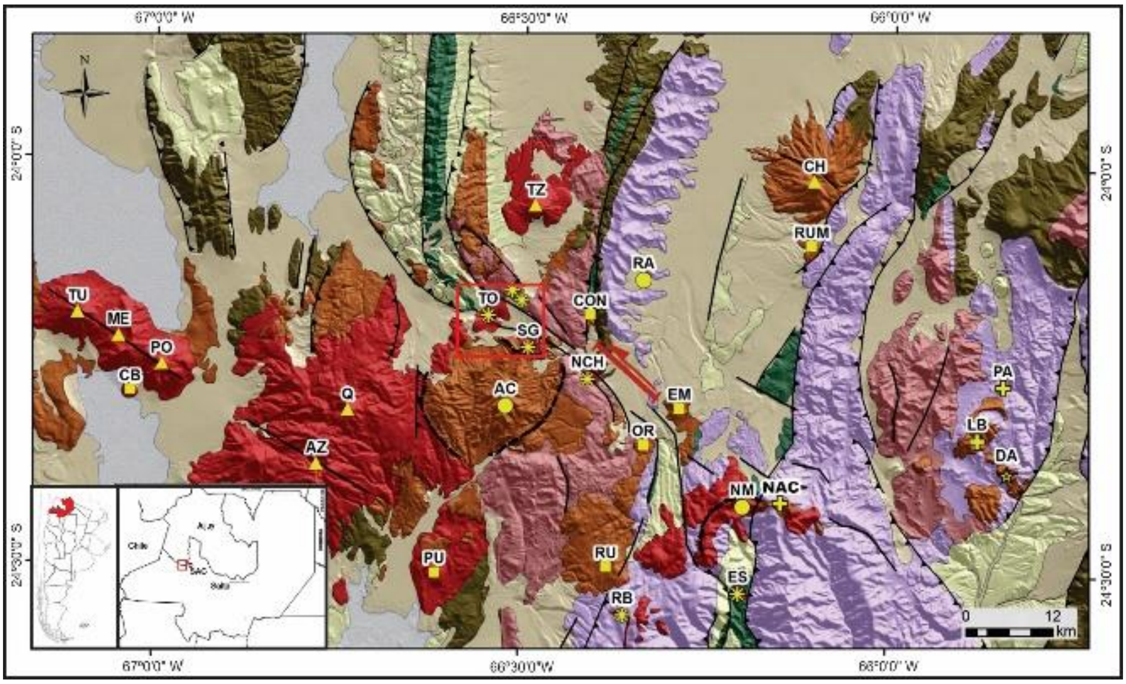

Figure 1: Geological map of the study area (from Norini et al. 2013). Red box indicates the area of study. Q: Quevar; AC: Aguas Calientes; NCH: Negro del Chorrillo; SG: San Gerónimo; TO: Tocomar; TZ: Tuzgle.

For this paper, we have adopted the method proposed by Garg and Combs (2015) for the reformulation of the volumetric method. This new method derives recoverable heat from specific power cycles (e.g. single-flash, binary), reducing ambiguities associated with reference temperature, by condenser temperature *(T_c)*, and conversion efficiency, while fluid properties are obtained from tables. Due to the uncertainty for determining the thermal recovery factor *(Rg)*, area *(A)*, thickness *(Z)*, and reservoir temperature *(T_R)*, each is assigned a probability distribution function. Therefore, the electric power of a geothermal field for a single-flash power cycle is defined by the following equation (see Table 1 for the meaning of the variables):

$$W_e = \frac{W_{Aflash} \cdot \eta_u}{Y \cdot f_{load}} \quad (1)$$

Where available work *(W_{Aflash})* is defined as:

$$W_{Aflash} = \frac{\alpha(T_R - T_{sep})}{h_{gl}(T_{sep})}\{h_{stm}(T_{sep}) - h_w(T_c) - T_{cK}[s_{stm}(T_{sep}) - s_w(T_c)]\} \quad (2)$$

Here:

$$\alpha = R_g V \rho_c \quad (3)$$

3.2 Parameter assignment

The variables used in equations (1), (2) and (3) were divided into two groups (see Table 1): specific reservoir parameters (Group I) and constant parameters related to the method (Group II). The parameters in the second group are related to plant conditions and can be accurately specified based on technical information (e.g. DiPippo 2012). The parameters in Group I depend on intrinsic properties and on the level of knowledge about each field, so uncertainty is larger. Therefore, a triangular probability distribution is assumed when there are minimum, most likely and maximum values (i.e. *A*, *T*), while a uniform distribution is assigned when all values within a certain range are equally probable (i.e. *Z*, *Rg*).

The following are the variables of Group I:

Area: This parameter was calculated semi-automatically by using Petrel (academic license), from the 3D magnetotelluric (MT) inversion model generated by Ahumada et al. (2017). Isoresitivity contours were drawn every 5 Ω.m, from 10 Ω.m to 30 Ω.m, and the surface enclosed by each of them was calculated (Fig. 2). According to Cumming (2000), the MT method resolves the geometry of the clay cap (<10 Ω.m) that forms immediately above the reservoir top. In this sense, the area enclosing the 10 Ω.m curve can be interpreted as the minimum reservoir area; however, some studies use higher values (e.g. 30 Ω.m; Rustandi et al. 2016). In order to maintain a conservative effect in the calculations, a biased triangular distribution towards the minimum values was assigned, with minimum (automatic detected) and most likely (semi-automatic) values corresponding to the 10 Ω.m curve, and a maximum value for the area of the curve of 15 Ω.m (Table 1)

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Specific reservoir parameters					
Variables	Units	Values			Distribution
		min	m.l.	max	
Area (A)	km^2	5	6	9	Triangular
Thickness (Z)	m	1000		1400	Uniform
Temperature (T_R)	ºC	184	200	229	Triangular
USGS "Heat in place" parameters					
Recovery factor (Rg)	%		0-20		Uniform
Volumetric heat capacity (ρc)	kJ/m^{3}K		2700		*
Separator temperature (T_{sep})	ºC		151.83		*
Condenser temperature (T_c)	ºC		40		*
Electric conversion efficiency (η_u)	%		75		*
Plant load factor (f_{load})	%		95		*
Years (Y)	years		30		*

Table 1: Parameters used to calculate the electric potential. (*) Data obtained from Garg and Combs (2015).

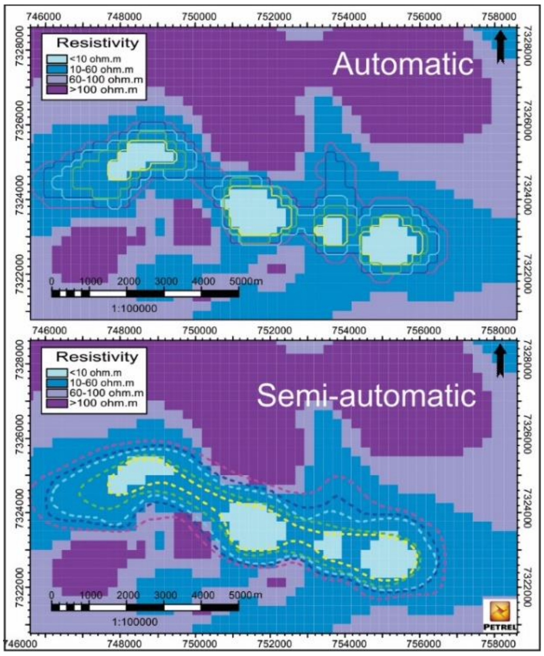


Figure 2: Slices at 3900 m a.s.l. showing the area enclosed by each method.

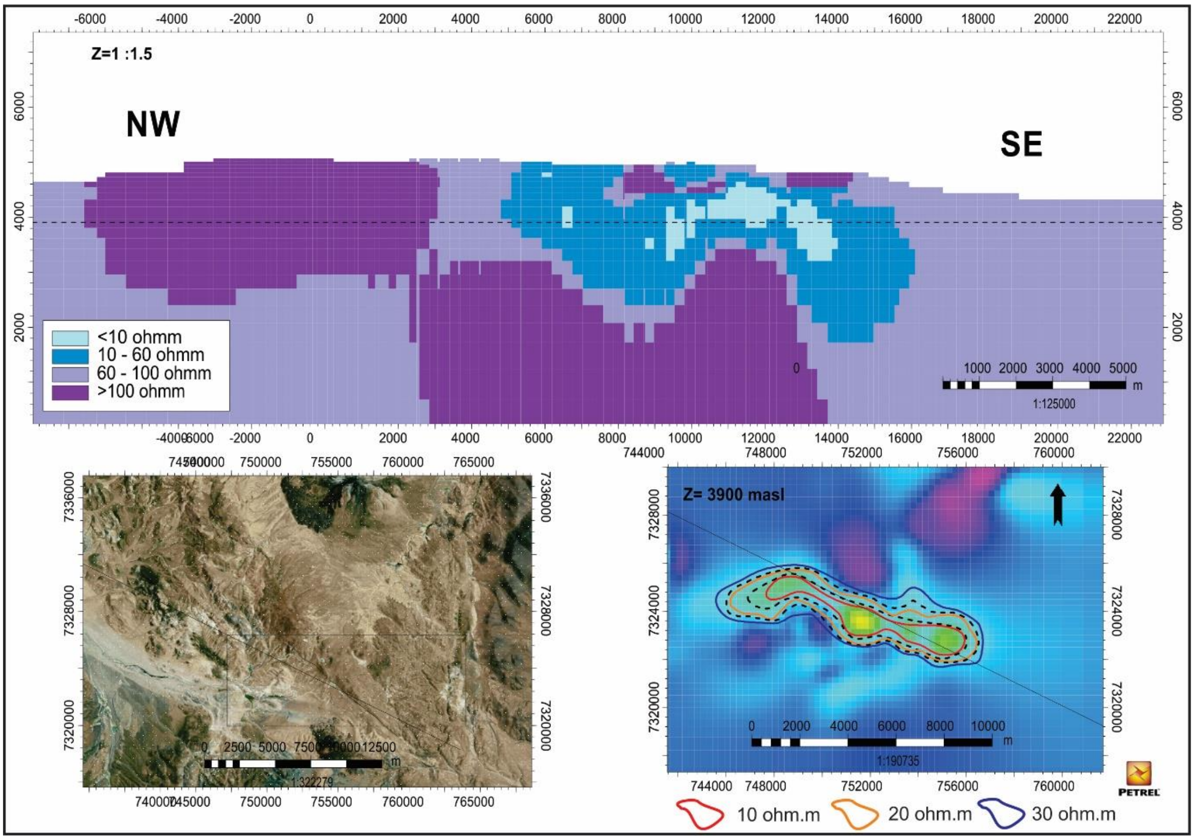
Thickness: Several slices were analyzed in order to correctly interpret the reservoir's resistivity anomalies and understand its geometry (Fig.3). As previously mentioned, <10 Ω.m resistivities are assigned to smectite-rich layers (argillic alteration). In the reservoir, associations of propylitic alteration (e.g. illite, chlorite) occur, and their resistivity ranges from 10 Ω.m to 200 Ω.m, although they commonly have values of 20 to 50 Ω.m (Melosh et al. 2010). Several property filters were applied under these criteria, and four areas with different resistivity ranges were determined: <10 Ω.m, 10-60 Ω.m, 60-100 Ω.m and >100 Ω.m. Once defined, average thicknesses were estimated to be between 10-60 Ω.m and 10-100 Ω.m; those values were used to assign a minimum and a maximum under a uniform distribution, since the reservoir is not a homogeneous body and its geometry varies within that range (see Table 1).

Reservoir temperature: The temperature used in the calculations was the one reported by Giordano et al. (2016), based on cationic and silica geothermometer measurements. Since the thermal emanations of Tocomar are sodium chloride in composition, Na-K-Ca geothermometers are recommended (Williams et al. 2008). Thus, a triangular distribution was assigned to the values, where the maximum is represented by the average temperature estimated from the potassium-sodium ($T_{K\text{-}Na}$) concentration ratio, and the minimum and most likely values of the temperatures estimated by silica geothermometers (T_{SiO2}) (Table 1).

Recovery factor: Following the hypotheses of Garg and Combs (2015), this factor was assumed with a uniform distribution between 0 and 0.2. These are recommended values for an exploratory phase assessment prior to drilling a well. The minimum value (0) represents the possibility that a potential well is not productive (absence of a permeable zone).

4. RESULTS

Several scenarios were assessed for electrical potential of the resource, taking into account different probability distribution functions (triangular, normal, uniform, truncated



normal, among others) for each uncertain parameter. Then, 50,000 simulations were run to obtain different forecasts.

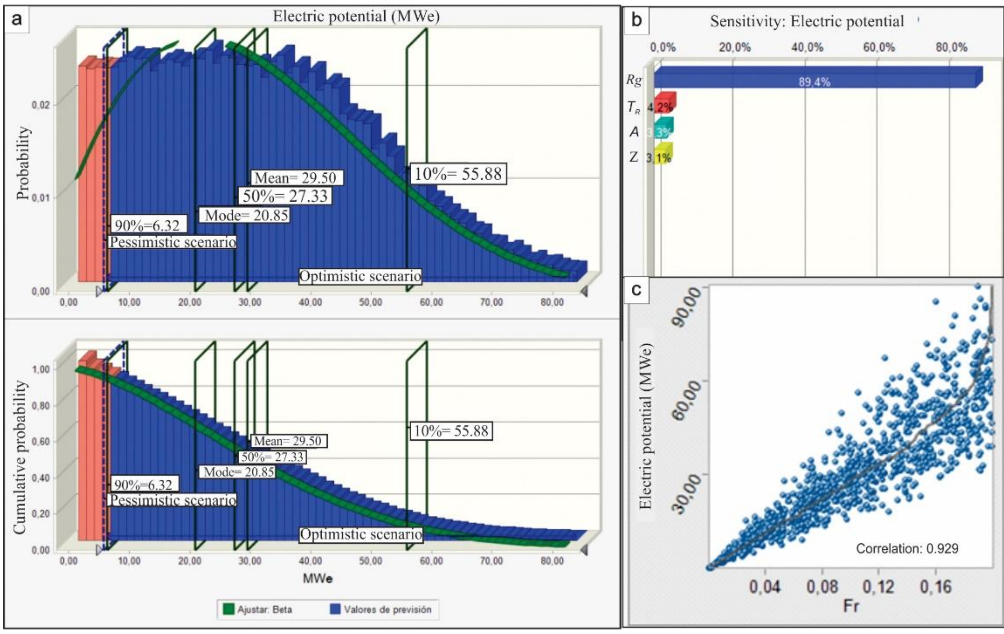


Figure 3: Graph showing the results of the probabilistic analysis of the data. a) Adjusted and accumulated frequency Beta curve. b) and c) effects of the recovery factor on the estimates.

Figure 3 shows the simulations histogram, together with a fitted Beta probability distribution (Fig. 4a). Although several distributions were tested, the Beta distribution offered a better fit under the AD (Anderson-Darling) hypothesis test. The fitted distribution has a mean of 29.37 MWe, a mode of 20.66 MWe and a standard deviation of 18.87 MWe. The exceedance curve shows that the P90 value is 6.17 MWe and, at the other end of the curve, the P10 value is 55.88 MWe (Fig. 4a). Through 50,000 simulations, we analyzed both the form of the distribution of the electric potential analyzed, and its sensitivity to the various parameters assumed as uncertain. We found that the parameter with greatest weight is *Rg* (Fig. 4b), which shows a strong linear correlation to the electric potential (Fig. 4c).

5. DISCUSSIONS AND CONCLUSIONS

5.1 Classification of the resource

According to Muffler and Cataldi (1978), geothermal resource base can be classified as geothermal resources inferred, indicated or measured reserves, according to the level of geological confidence and the degree of technical and economic assessment. However, the Australian Geothermal Reporting Code Committee (AGRCC 2010) states that the term "reserves" is restricted to resource assessments that have considered modifying factors affecting the chances of commercialization. Also, based on the exploratory results and the confidence level in the estimates, geothermal resources are subdivided into inferred (indirect measurements), indicated (indirect measurements) and measured (production tests). Since the reservoir conditions and dimensions were determined through geological, geochemical (Giordano et al. 2016) and geophysical evidence (Ahumada et al., 2017), the estimated resources for the Tocomar geothermal field can be classified as inferred resources and should be analyzed as such.

5.2 Potential of the Tocomar Geothermal Field

Although there are different methods for assessing geothermal resources (e.g. heat flow, power density), the volumetric method combined with Monte Carlo simulations continues to be one of the most widely applied in the exploration stages. However, being based on indirect measurements, the method has its limitations, and thus results must be analyzed in terms of probability of occurrence.

Based on the results expressed in Figure 4, it can be inferred that the Tocomar Geothermal Field presents a 90% probability (P90), or higher, of generating at least ~6 MWe (worst-case scenario), a 50% probability (P50) of generating no less than ~27 MWe, and a 10% probability (P10) of generating ~56 MWe (minimum certainty or optimistic scenario). As for the central tendency parameters, the most repeated value after 50,000 iterations (mode) was ~28 MWe. Data from the sensitivity analysis on Figure 4b shows that the recovery factor (Rg) is the most sensitive variable regarding calculations of potential. This effect is evidenced in Figure 4c, which shows that there is a linear correlation between the Rg and the calculated electric potential. This occurs because the recovery factor relates the heat stored in the reservoir to that available on the surface; therefore, it varies from field to field and is subject to the performance of the wells.

Finally, the data presented in this paper and the estimates made by Carrizo 2016 (28-35 MWe) for the Tuzgle geothermal field (12 km North), together with the strategic position of the Tocomar Geothermal Field (located on National Route 51, C-14 Railway, and crossed by the Chile-Argentina high voltage line), identify the Tuzgle-Tocomar Geothermal Area as one of the most favorable for the development of renewable energies.

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Figure 4: Graph showing the results of the probabilistic analysis of the data. a) Adjusted and accumulated frequency Beta curve. b) and c) effects of the recovery factor on the estimates.

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