Resource assessment of the Tecuamburro geothermal system using reservoir simulation

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ABSTRACT

The Tecuamburro geothermal area is located in southeastern Guatemala along the Central American chain of volcanos. Thermal surface manifestations are found over an area of nearly 400 km^2. Major hot springs and fumaroles are located at Laguna Ixpaco, along Rio Los Esclavos, and east and northeast of the volcano. Geothermometry analysis of these manifestations yields temperatures of 150 – 300ºC. Previous work done by Los Alamos National Laboratory, the US Geological Survey, and the Instituto Nacional de Electrificacion in geology, geochemistry, geophysics, and the drilling of one cored well, named TCB-1, suggests that there could be a promising geothermal resource. The geoscience information was reviewed, the conceptual model was updated, and a digital conceptual model was developed to create a new reservoir model. This paper describes the model creation based on our geothermal modeling framework; this model can be run either in AUTOUGH2 or Waiwera. The new model integrates geology, geophysics, faults or structures, alteration zones, reservoir engineering and drilling data, resulting in a robust reservoir model. The model produces good results in matching the temperature profile of well TCB-1, surface features, and temperatures below the clay-cap in Tecuamburro and Infiernitos. Base on this new model, an uncertainty quantification analysis was performed with 1000 sample models for the natural state. The models were filtered based on the temperature profile of the well and temperatures below the clay cap using Approximate Bayesian Computation (ABC) resulting in 100 acceptable sample models that were used to perform a resource assesment applying an innovative method that ran each filtered model for a maximum potential production scenario over 25 years. Results provided by this novel approach give a resource assessment that includes the same information used in traditional stored heat calculations but also takes account of reservoir and wellbore physics and a realistic energy extraction and injection strategy, thus providing a more accurate forecast.

1. INTRODUCTION

1.1 The Tecuamburro geothermal area

Work done by Los Alamos National Laboratory, the US Geological Survey, and the Instituto Nacional de Electrificacion in areas such as geology, geochemistry, and geophysics (Duffield et al., 1990; Janik et al., 1992) back in the 90s suggests that the Tecuamburro area hosts a promising geothermal resource. The Tecuamburro Volcano is located along the Central American volcano chain in southeastern Guatemala. Thermal manifestations that can be found over an area of around 400 km^2 are linked to recent volcanic activity. Most of these springs and fumaroles are located at Laguna Ixpaco, along the Rio Los Esclavos, east and northeast of the volcano. These manifestations yield geothermometer temperatures of 150 to 300ºC (Janik et al., 1992). To obtain subsurface information and support further development, a geothermal gradient cored hole TCB-1 was drilled at the southern part of Laguna Ixpaco, encountering temperatures of 238ºC at 795 m from the surface. The temperature profile corresponds to conductive heating.

As part of the exploration program, a magneto-telluric (MT) survey campaign took place in 2005 over an area of 9 km^2 centered at the northwest part of Laguna Ixpaco. Analysis of data suggests a three-layered resistivity structure: a shallower high resistivity layer of about 10 to 30 Ω-m, an intermediate low resistivity layer of less than 10 Ω-m (clay-cap), and a deep high resistivity layer with values of apparent resistivity bigger than 20 Ω-m at the northwestern part of the survey that may indicate a higher temperature zone (up-flow). The survey revealed three resistivity discontinuities that can represent faults and/or fractures that are not traceable to the surface. These discontinuities align with fumaroles at Laguna Ixpaco and with the direction of the field stress (Japan External Trade Organization, 2006).

At early stage exploration, as in a greenfield development, every activity reduces uncertainty about subsurface conditions and thermal potential. Assessing the potential of a geothermal resource is important since it is a crucial step in obtaining the funds needed to continue the development of the resource. The geothermal industry uses methods, such as stored heat or power density (Grant, 2015; Holmes, 2024), which possess drawbacks and inaccurate assumptions but are suitable for the scarce or limited information available at this stage. For mature fields, reservoir modeling is an invaluable tool for managing and assessing the resource, with the important criteria of having a good model calibrated to a natural state and transient production data (O'Sullivan et at., 2001).

Creating reservoir models is one of those activities, involving a multidisciplinary approach and different data sets that are synthesized into a physics-based representation of the geothermal system. Recently, O'Sullivan et al., 2023, proposed a geothermal modeling framework (GMF) for creating robust, reliable, mesh-independent framework for working with reservoir models. The uncertainty in exploring a greenfield is significant and this affects the reservoir model that could represent the geothermal system at this stage. Recent developments in the field of uncertainty quantification (UQ) and resource assesment (RA) in reservoir simulations by Dekkers et al., 2022; Gravatt et al.,

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2023., have established the successful application of UQ and RA using reservoir simulation by creating thousands of models that could be a representation of the geothermal system constrained by the best current understanding of the reservoir, and finally running filtered models to simulate a probable production scenario. Reservoir and well physics are used to create a realistic production and injection scenario that provides a more accurate probabilistic range of the geothermal system power potential.

This paper focuses on two aspects of resource assessment. First, developing a new reservoir model for the Tecuamburro geothermal area using our geothermal modeling framework, and second, quantifying the uncertainty of the data used for model calibration and running 100 production scenarios for 25 years to provide a more robust probabilistic estimate of power potential output of the Tecuaburro geothermal system.

2. METHODOLOGY

2.1 The new model

Geothermal modeling for the Tecuamburro geothermal system was focused on matching data of some features of the conceptual model, such as the fault system, clay cap (alteration zone), temperatures in well TCB-1, and surface features. The model was set up to be able to run in the highly parallelized simulator Waiwera (Croucher et al., 2020); this parallel power allows faster simulation times (Croucher et al., 2018) and the ability to run thousands of models in parallel on high-performance computing cloud nodes such as NeSI, Azure or AWS.

2.2 Digital conceptual model

Tecuamburro conceptual model has improved over the years. As part of this study, all the geoscience information was reviewed, and the integration of magneto-telluric data helped to develop a new conceptual model, set up as a digital, conceptual model in LeapFrog Energy®. Previous models, such as the ones proposed by Janik et al., 1992 and JETRO., 2006 were used as a base for the updated model proposed in this study. Key features of the new conceptual model are discussed briefly here.

Geological and structural model

Tecuamburro geothermal area is believed to host two separate geothermal systems: one informally called Tecuamburro and the other Infiernitos (see Fig. 1). Tecuamburro and Infiernitos lie within an N-S trending, 20 km wide graben. The Jalpatagua strike-slip fault zone terminates the graben at the north, and the Pacific coastal plain sediments bury the southern end. This area contains several older volcanoes that range in age from >1.8 Ma to 0.8 Ma, including Piedra Grande, El Sordo, and Los Sitios. These volcanos contain large areas of hydrothermal alteration, arcuate crater rims, and collapse features, and a large crater or caldera informally named the "Chupadero" crater. These volcanoes are crossed by N and NW-trending normal and reverse (thrust) faults.

Heat source

The inferred heat source of the Tecuamburro geothermal system is magmatic. The changes in resistivity from low to high at around 1500 m in depth at the northwestern part of Chupadero Caldera (see Fig. 1) may suggest the presence of parental ascension fluid. The heat source could be related to a volcanic intrusion that may correspond to a series of phreatic explosions that formed Laguna Ixpaco around 2.9 Ka, indicating a young heat source (Duffield et al., 1990). Infiernitos geothermal systems lie on the Piedra Grande volcanic complex with a suggested age of about 1.2 Ma (Duffield et al., 1990). The majority of this volcano is hydrothermally altered, mostly located near Finca Las Delicias, where a fumarole informally called Infiernitos may represent a larger but relic hydrothermal alteration event (see Fig. 1). Similar to Tecuamburro, the inferred heat source is the magmatic center around the fumarole.

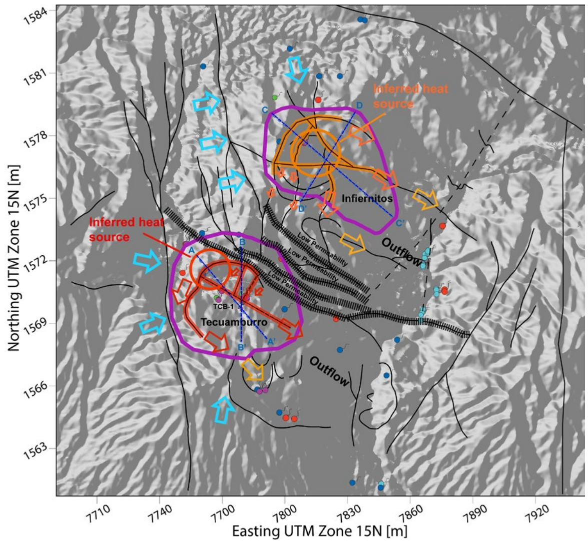

Figure 1. Tecuamburro geothermal area. Plan view of the updated conceptual model with topography, structures, the interpreted clay-cap for Tecuamburro and Infiernitos (thick magenta line), upflow structures (red and orange highlighted faults), inferred outflows (red and orange arrows), and inferred cold water recharge (blue arrows).

Clay cap (alteration zone)

Well TCB-1 was drilled south of Laguna Ixpaco in 1990 with a total depth of 808.35 m. Well stratigraphy shows inter-bedded tuffs and avalanche deposits from the Tecuamburro complex, mixed pyroclastic and volcanoclastic rocks, and andesite flow. From 253 to 791 m from the surface of the andesitic sequence, mostly lavas, are intensively chloridized with low permeability. The pore space of the core samples is filled with hydrothermal minerals, and this interval represents the clay cap thickness in this part of the system. MT data and the resistivity distribution with depth agree with core data. The MT survey campaign covered an area of 9 km^2; the resistivity anomaly is not well constrained, and the approach of extending the clay cap was used in order to represent the temperature distribution and surface features. The best temperature log of TCB-1 shows a conductive heating profile in accordance with the well's stratigraphy (see Fig.2).

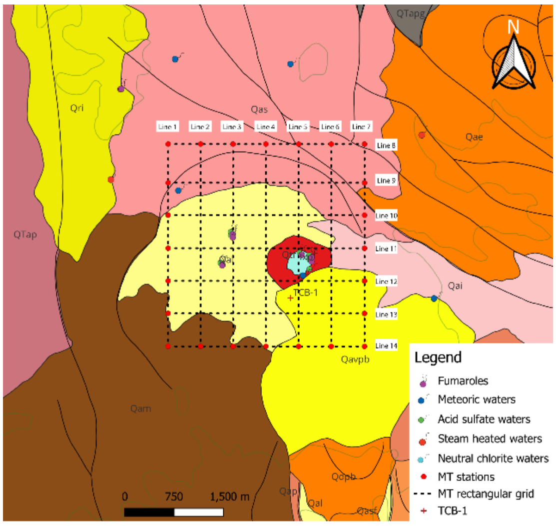

Figure 2. Tecuamburro MT stations and rectangular array. Geologic map units, Laguna Ixpaco, fault system in black solid lines, and hot-springs for reference.

For the Infiernitos geothermal system, the only information related to a resistivity anomaly comes from a series of vertical electrical surveys (VES) that INDE acquired from June 1985 to May 1986 covering most of the Tecuamburro graben area with 153 stations of arrays with AB/2 from 3 to 2000 meters, together with field information suggesting that the majority of the volcanic complex of Piedra Grande is hydrothermally altered, a clay-cap extension was assumed and imposed in the conceptual model.

2.3 Model design

A numerical model was created based on the information from the digital conceptual model. Versions of the model were created for AUTough2 and Waiwera; model dimensions are 22×25x 4.5 km, with a total number of 109058 blocks. Key features of the model are discussed as follows:

Rock type distribution

Rock type distribution was couple with information from the didital conceptual model. In the Tecuamburro graben all lithologies maped were assigned to the simulation grid blocks as can be appreciated on Figure 3.

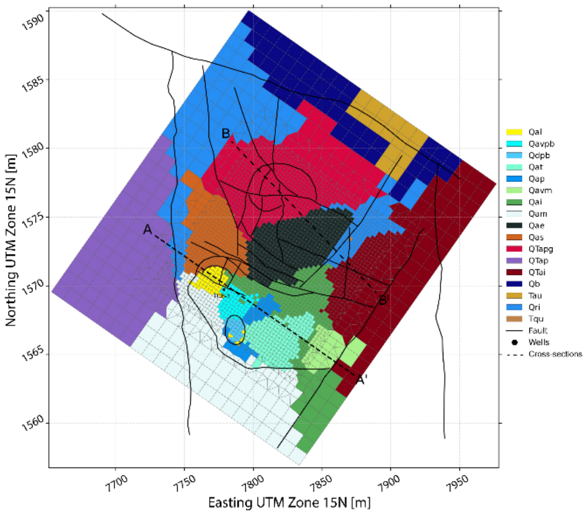

Figure 3. Rock type distribution for the Tecuamburro graben to all grid cell in the simulation grid.

Fig. 4 a) shows the rock type distribution for faults. The model has a total of 885 different rock types (blocks that represent different lithologies, faults and/or intersections, alteration zones, and "clay cap"); this approach allows a high degree of control, changing parameters of permeability distribution as needed to match field data. Fig. 4 b) is a 3D representation of the faults in the model over the simulation grid for reference.

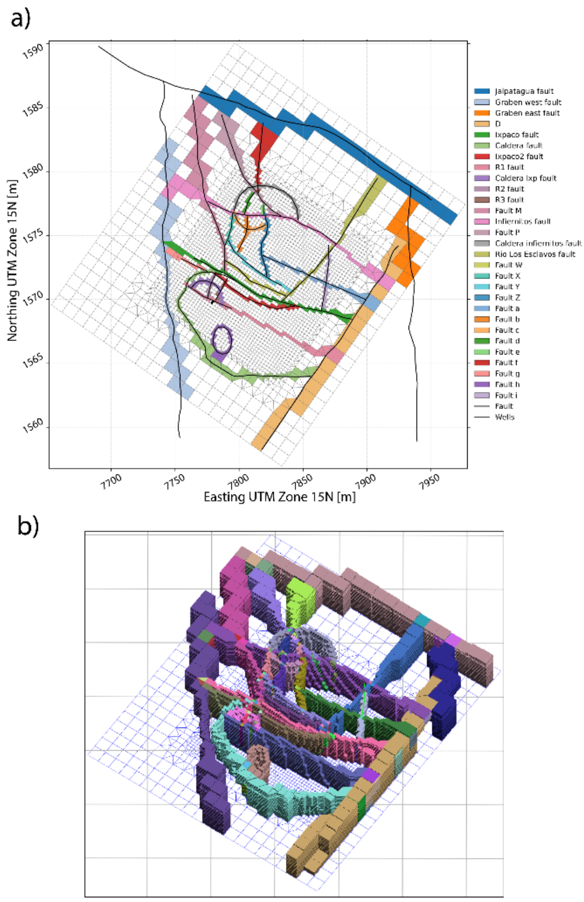

Figure 4. a) Simulation grid and faulted blocks (rock type) at the bottom layer of the model. b) 3D representation of faults in the model.

Permeability distribution

Permeability distrubition for the reservoir model was assinned based on the digital conceptual model and iterated durign the calibration process. Fig. 5 a), and b) shows the vertical permeability for both systems Tecuamburo, and Infiernitos in the z-direction (NW-SE) cross-section A-A' and B-B' (see Fig. 3) for Model TC109058_030.

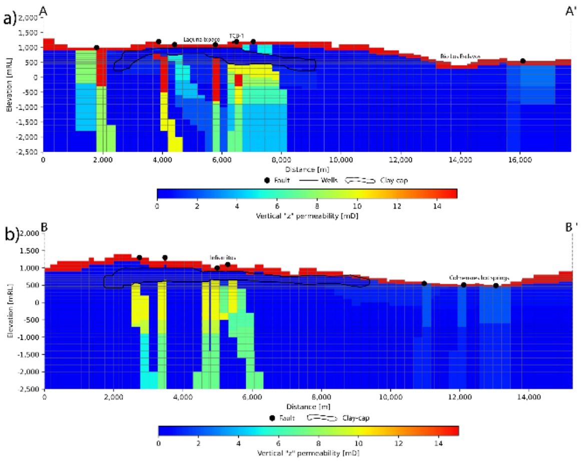

Figure 5. a) Vertical permeability on the NW-SE cross-section A-A' for the Tecuamburro geothermal system. b) Vertical permeability on the NW-SE cross-section B-B' for Infiernitos geothermal system. For model TC109058_030

Boundary conditions.

Natural recharge of mass and heat are specified at the bottom of the model, and a background conductive heat of 70 mW/m^2 was applied. The best-fit match for the model was achieved with a total hot mass input of 122 kg/s with an average enthalpy of 1200 kJ/kg. Natural recharge of rain was applied to surface blocks based on the local rain precipitation history and an appropriate infiltration rate. Top boundary conditions with atmospheric conditions were applied for ambient temperature and pressure. The model is set to run with the "water-energy-air" equation of state.

2.4 Natural state model

The first stage of reservoir modeling is the calibration of a natural state model that represents the system in a pre-production state (O'Sullivan et al., 2001; O'Sullivan & O'Sullivan, 2016).

Objectives of the natural state model were:

1. Match the field data from TCB-1, such as temperature and pressure distribution.

2. Good agreement characteristics of natural surface features such as temperature and flow.

3. Represent the main flow paths, upflows, outflows, and barriers as detailed in the conceptual model.

4. Represent with good agreement temperatures below the clay cap. For the Tecuamburro and Infiernitos geothermal systems, a constraint in temperature below the clay cap was imposed to be in the range of 200°C and 150°C, respectively.

The parameters adjusted during the natural state were deep upflows of mass, permeability, and porosity of the various rock types.

2.5 Uncertainty quantification analysis

In geothermal simulation problems and especially in early-stage development, the uncertainty of a model is significant due to the scarce data available for calibration. The Approximate Bayesian Computation approach has demonstrated effectiveness in real-world geothermal data sets, providing accurate parameter estimates and capturing the uncertainty of the model parameters. ABC allows for the incorporation of different data sets, such as geophysics, temperature, and pressure, which is ideal for the exploration stage in geothermal development (Gravatt et al., 2023). For this study, 1000 models were created randomly constrained by the best-fit model and adhering to geological principles (De Beer et al., 2023). The models were then run to a steady state, and the uncertainty quantification analysis of the temperatures for well TCB-1, temperatures below both clay caps were analyzed and constrained by the ABC approach. Table 1 shows the prior mean and standard deviation for the posterior distribution of the uncertain model parameters to be tested.

Table 1. Tecuamburro best model match (prior mean) and range of uncertainty parameters with the standard deviation.

Tecuamburro model parameter	Prior mean	Standard deviation
Rock permeability	5.0e-12 to 1.0e-16 m-2	(of log-permeability) 1 m-2
Rock porosity	0.03 to 0.25	0.25
Total upflow rate	122 kg/s	30 kg
Total enthalpy	1257 kJ/kg	33.3 kJ

2.6 Resource assessment

After the implementation of ABC approach to filter the reservoir models based on the geophysical data available and the objective function; an innovative method developed by Dekkers et al., 2022, was used to estimate and run production scenarios to a maximum power potential. For the Tecuamburro geothermal system 100 filtered models that reached a steady state were used. The models were simulated for a 25-year period of future production and injection, using a typical flash power plant configuration and a range of power outputs were obtained.

The method described before is an iterative algorithm that selects the best targets for production and injection for any given sample model. The algorithm continues selecting targets and creating wells until the additional energy produced by the next well is less than 5% of the previous iterative step indicating diminishing results from adding a new well. Wellbore modelling is used to accurately describe the thermodynamics and fluid mechanics of each production well used in this approach.

The objective of this method is to calculate the production potential for each sample model in an efficient way allowing the use of specific thresholds, such as pressure support if needed. The algorithm runs each model until it reaches the maximum production scenario possible within the limitations imposed previously in our production setup.

3. RESULTS

3.1 Natural state model

Results of the best-fit model for the temperature profile of well TCB-1, when compared with field data, were in good agreement, reflecting the conditions of a conductive heating profile that was encountered upon drilling in a low permeability area (see Fig. 6).

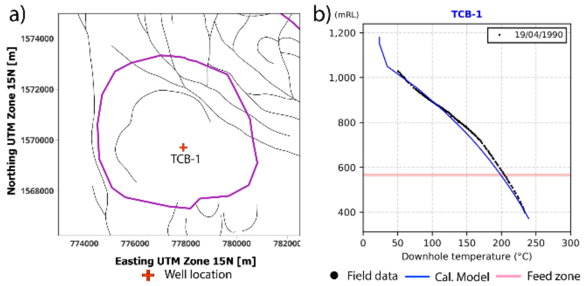

Figure 6. Location of TCB-1 in the Tecuamburro area (left of figure), and summary plot of the temperature profile in black dots (field data), the best-fit model in solid blue, feed zone allocation on pink solid line (right of figure).

The temperature distribution across the reservoir agrees with the conceptual model for both systems. In the high enthalpy Tecuamburro area, the modeled upflow rises on the NW part of Laguna Ixpaco, reaching the clay cap and then outflows with the direction southeast (see Fig. 7).

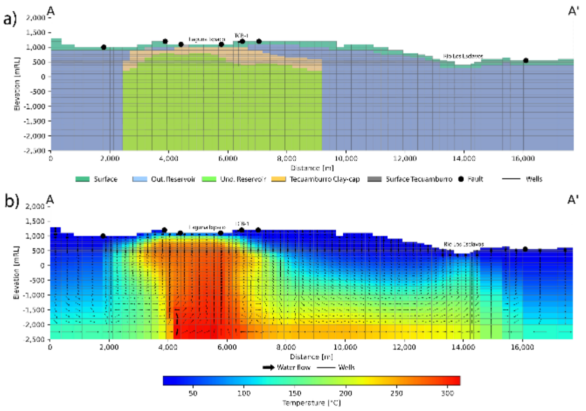

Figure 7. a) Rock type distribution for the Tecuaburro geothermal system. Clay-cap blocks (yellow) and blocks under clay cap (green) with enhanced permeability. b) Natural state temperature distribution in the model on the NW-SE cross-section A-A'. Arrows indicate direction of mass flow and the convective heat flow.

For the Infiernitos lower enthalpy area, the modeled upflow rises at the center of the caldera through the NW normal fault, informally called "Small Infiernitos fault," reaching the clay-cap and then outflowing in the southeast direction and feeding the Colmenares host-spring area (see Fig.8).

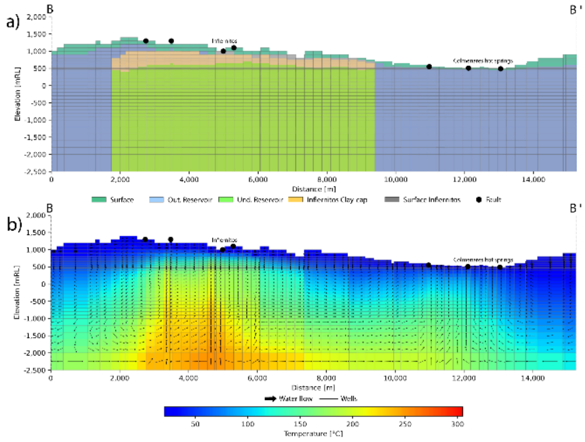

Figure 8. a) Rock type distribution for Infiernitos geothermal system. Clay-cap blocks (yellow) and blocks under clay cap (green) with enhanced permeability. b) Natural state temperature distribution in the model on the NW-SE cross-section B-B'. Arrows indicate direction of mass flow and the convective heat flow.

3.2 Uncertainty quantification analysis.

The results of ABC filtering were constrained to the best 10% of models. Fig. 9 b) shows well TCB-1 temperature profiles for the 1000 models simulated and, in red, the filtered models.

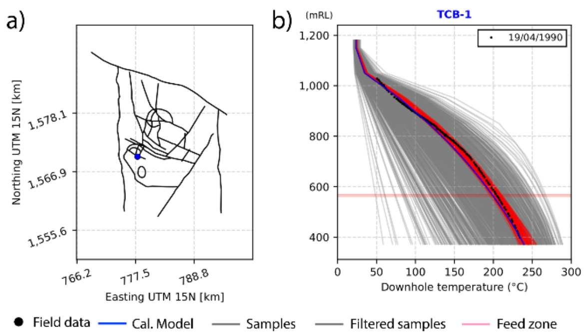

Figure 9. a) TCB-1 location over map plan view. b) UQ analysis for temperature profile. 1000 models simulated in grey solid lines, best 10% in red solid lines.

For the Tecuamburro system, most of the blocks below the clay cap range from 180 to 200ºC, in accordance with the formation process of rock-fluid interaction that changes the rock into clay (Dekkers et al., 2022). For the Infiernitos system, the temperature below the clay cap for the majority of the blocks is in the range of 140 to 160ºC, which was the threshold for a relic and low temperature system at the north part of the Tecuamburo area (see Fig. 10).

Fig. 10 b) shows the statistics for hot mass and enthalpy that produced the best matches for the sample models.

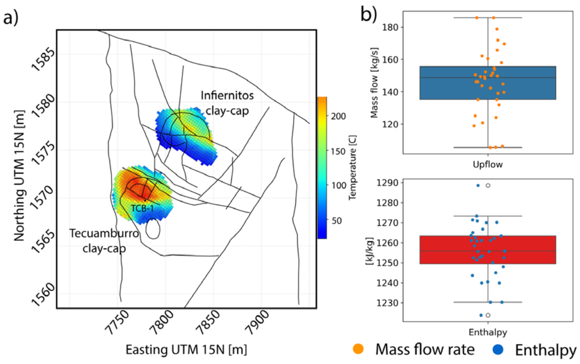

Figure 10. a) Model area, fault system, and location of well TCB-1 in blue. The temperature below the clay cap in both the Tecuamburro and Infiernitos systems. b) Summary plot of the statistics of mass flow rate (blue boxplot) and enthalpy (red boxplot) of the filter samples that better match field data; scatter data of both filters are plotted in orange and blue, respectively.

3.3 Resource assessment results.

Results of running the 100 samples produced probabilistic power outcomes that are constrained by filtering models that best match our current understanding of the geothermal system. Fig. 11 shows outcomes of the resource assessment in the Tecuamburro geothermal system. Results of the simulations suggest that the most probable power output for this geothermal system with a P90 confidence interval is around 25 MW-Net. For the confidence interval of P10 the power output is estimated to be around 40 MW-net.

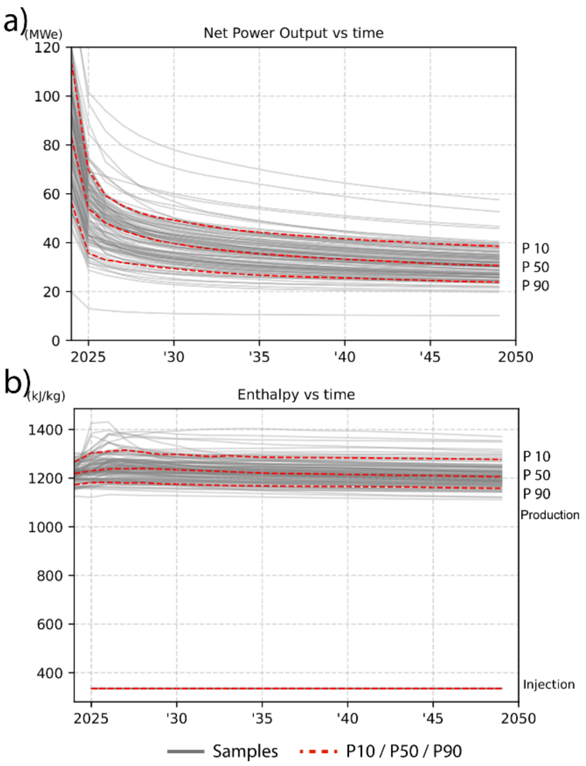

Figure 11. a and b) Summary plots of 100 models run for 25 years (grey solid lines) for net power and flowing enthalpy for each scenario. The uncertainty bands indicate the P90, P50 and P10 confidence intervals (dotted red lines).

One interesting result of the simulations is the stable flowing enthalpy in all production scenarios. These results might be related to the fact that most of the injection takes place according to the algorithm to the south of the system where there are no faults that could directly link the injection to the production area and thermal breakthrough was minimal after 25 years of injection.

4. DISCUSSION

The development of a new and novel reservoir model for the Tecuamburro geothermal area using the geothermal modeling framework proposed by O'Sullivan et al., 2023., has created a state-of-the-art, industry best-practice reservoir model. The model explicitly integrates geology, geophysics, and reservoir engineering data into a numerical representation of two complex geothermal systems.

The model agrees with the temperature data from well TCB-1, and the temperate distribution with depth agrees with the conceptual model. Model results for the surface features were mixed; surface blocks at Laguna Ixpaco and the Chupaderro caldera are in good agreement with hot springs and fumaroles, and the same results were achieved with the blocks at Infiernitos. Surface blocks representing the informally called Ixpaco fault, which is a hydraulic barrier between the two geothermal systems, have a higher temperature than the threshold.

Modeled temperature results for both clay caps have some discrepancy, especially at the edges where temperatures are colder than the limit, but overall, the results are in good agreement with the conceptual model and the threshold temperature for both systems.

The uncertainty quantification analysis for the Tecuamburro reservoir model has provided a good range of possibilities that can reproduce a reasonable model, mainly providing a range of hot mass input into the system. The same is true for the permeability and porosity of the different rock types. Since this is a mathematical representation of a complex natural system, the possibilities that satisfy the problem may not be realistic, even with the most expert knowledge or following geologic consistent rules. This reservoir model was created with data acquired in the exploration stage of geothermal development and there is a lot of uncertainty with the model outcomes, even after assessing model simulations with the ABC method and applying a UQ analysis.

The resource assessment produced interesting results compared with traditional techniques such as stored heat calculations. According to previous analysis made by JETRO in 2006, their computed power potential shows a range from 20 to 220 MW, with a probability distribution of more than 70% of confidence around 50 MW of power output. Our approach shows more conservative numbers, in the range of 25 MW based on reservoir physics and probable production and injection estrategies.

5. CONCLUSION

The model achieves good agreement with most of the field data and the conceptual model for both systems, and in this respect the model achieved the objective. The model can be easily updated with new information as all information is stored in a standard format and thus a model update can be performed fast due to the standardization of the workflow.

Our new method for carrying out resource assessments of geothermal systems during the exploration stage has been used in many green fields around the world. The method uses the same available data that many geothermal developers have at the exploration stage, but leverages new geothermal modelling and uncertainty quantification technology to include reservoir physics, wellbore thermodynamis and fluid mechanics, and realistic energy extraction scenarios.

The UQ analysis concludes that there is a need to incorporate more variables into our workflow such as geochemistry, and we are working on incorporating the geochemistry data set in constraining model outcomes (more to come in the next few months).

Another important conclusion of this study is the need to carry out an extended magneto-telluric campaign in both systems, Tecuamburro and Infiernitos. If acquired the new information will improve the understanding of the resource by providing the extent of the clay-cap and defining the boundary for both systems.

5. FUTURE WORK

Currently we are working on including additional exploration data sets on our workflow:

- Geochemisty data such as geothermometers and surface features chemistry.
- The use of produced fluid chemistry over time to constrain the production scenario and by so, improving the future scenarios.
- The use of seismic data that is collected in many basin and range geothermal systems.

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