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Case Study: Numerical Model of San Vicente Geothermal System, El Salvador

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ABSTRACT

A case study of a numerical model for high-temperature liquid-dominant reservoirs in volcanic settings is presented. The natural state of the geothermal system was replicated in 2023 with TOUGH2 simulator, based on the conceptual model of the field, geoscientific updates and measurements in existing wells. Nevertheless, it was systematically reviewed during the history match of the first 15 months of production, utilizing iTOUGH2 inverse capabilities, and is the version presented in this paper. The results indicate that the geothermal fluid circulation depends mainly on the existing faults and suggests that limited natural recharge from the surroundings is to be expected, in accordance with the lumped parameter model of the system. By the end of 2024, several forecasts based on different operation regimes in upcoming years were simulated, providing specific inputs for field management. Two of them are presented, suggesting that current operation rates can be sustained in time, but that future expansion would preferably be stepwise to reassess the field evolution. As a particular contribution, a specific location for a secondary outflow of the reservoir at depth has been proposed as probable cause of the sharp thermal differences in wells of the northeast region.

1 INTRODUCTION

The Central American isthmus is located on the western limit of the Caribbean plate, with a volcanic arc due to the subduction of the Cocos plate, showed in Figure 1, which crosses through the middle of the country of El Salvador in a WNW-ESE direction forming the Central Graben structural depression and a zone of faults normally divided in five segments. On top of the middle segment, called the “San Vicente Fault”, the second most voluminous volcano of El Salvador was developed, named San Vicente Volcano or “Chichontepec” in the indigenous language “Nahuat” (Rotolo, 1998).

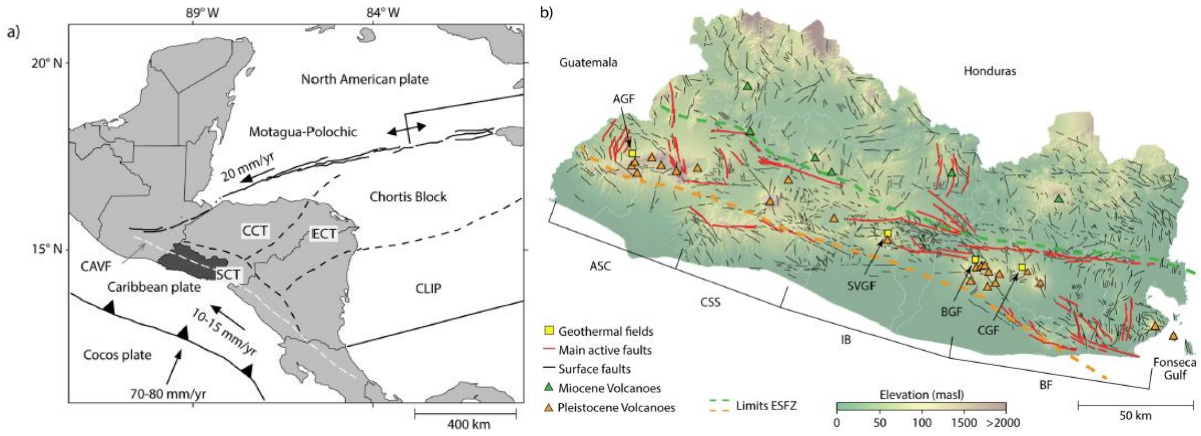


Figure 1: El Salvador tectonics and SVGF location (Salalá et al., 2024)

In the 1960s, with support of the United Nations Development Programme, a geothermal potential was detected under its northern flank near fumarolic areas. The drilling of two gradient wells and the first deep well confirmed the existence of the resource by 1979. LAGEO company obtained the concession of the project in 2004, between 2006 and 2015 drills seven new wells and, in 2020, updates the conceptual model of the field based on the extensive studies from geology, geochemistry, geophysics and revised well-measurements gathering the

understanding of the main elements of the geothermal system (LAGEO, 2020). The successful generation of electricity in San Vicente Geothermal Field (SVGF) started in August 2023 with a 5 MWe backpressure turbine, operating to this day.

Along with the start of commercial electricity generation, a numerical model of the geothermal system was developed to serve as a more robust framework than its predecessor (LAGEO, 2017). Firstly, it aimed to replicate the natural state of the geothermal system (Ribera, 2023), then matching the brief production history and eventually provide future forecasts under different field development alternatives and operation configurations. This paper summarizes the publication of the second version of the numerical model in December 2024 (LAGEO, 2024a).

2 NUMERICAL MODEL SETTINGS

2.1 Simulation and calibration process

TOUGH2 simulator (Pruess et al., 1999) was used in "forward" mode, manually setting multiple correlations (of permeabilities, rock distributions, heat source flow and sinks) in order to match the natural state and production history. With the gathered understanding of the best ranges for each variable, its correlations and sensitivities, the complementary iTOUGH2 (Finsterle, 2007) inversion capabilities were used to minimize the differences both to the natural state formation conditions along the well-tracks and to the monitored flowing enthalpies and pressure drawdown during the production stage (Figure 2).

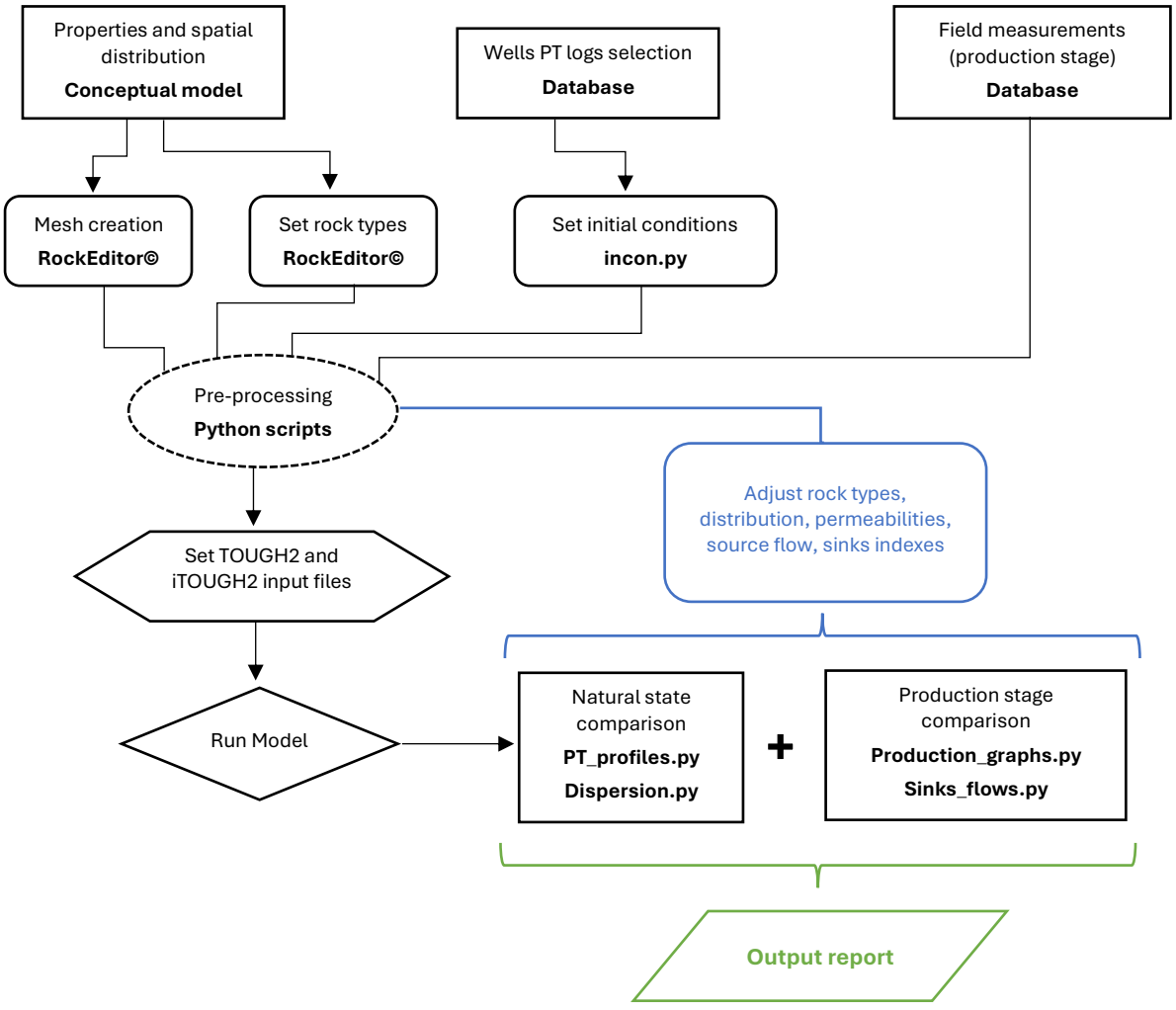


Figure 2: Diagram of simulation and calibration process

2.2 Mesh, Layer- and Rock-distribution

The extent of the model, in NAD27 latitude and longitude coordinates, is from 272'500 to 283'000 m North and from 512'000 to 524'000 m from west to east, englobing a 12.0 by 10.5 km area that surpasses by 1.5 km the southern limit of the concession area (orange line in Figure 3), since "it is desirable that the model domain extends a large distance beyond an actual or potential well field, so that fluid supply to the wells is governed by flow in the domain that is modeled, rather than by artificial or poorly known boundary conditions" (Pruess, 2002).

Using the islandic software "Steinar" (Vatnaskil, 2023), a rectangular (near square) mesh was selected for the far-field, with a spacing of around 500 m, and for the probable area of the resource a honeycomb distribution, composed of ~150 m hexagons. The top layer of the model reaches +600 m.a.s.l. (meters above sea level) and the bottom -2500 m.a.s.l. The volume has been distributed in 19 layers, each with 1414 elements for a total of 26'866 blocks. The static water-level, lithology, geophysical surveys and location of feed-zones for the existing wells help to define the number and thickness of the layers (Figure 3).

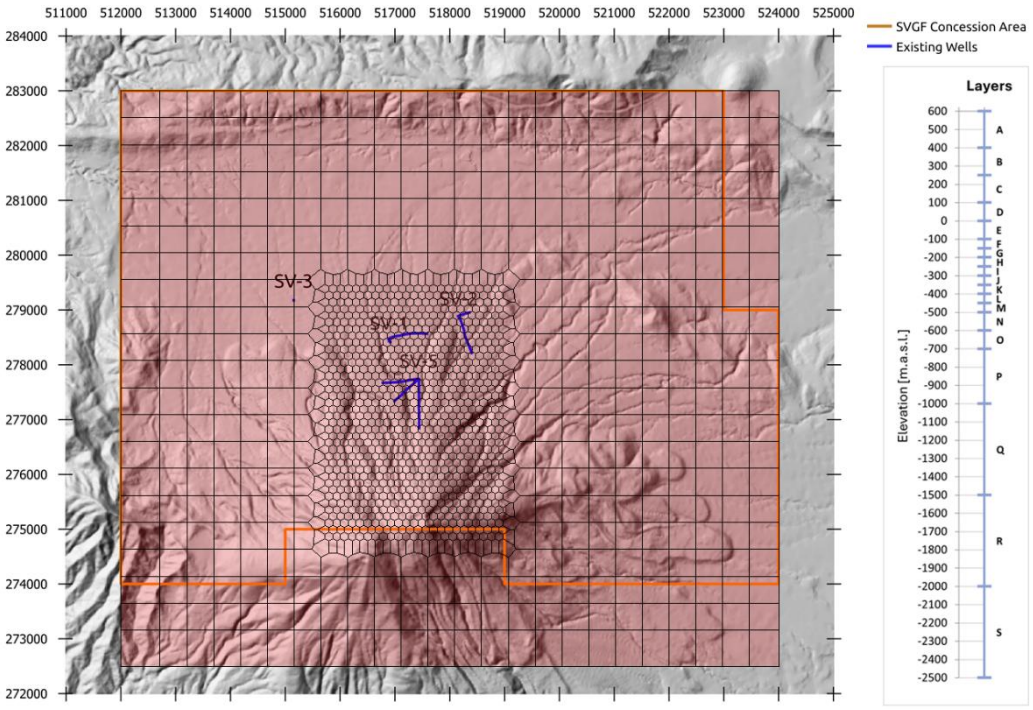


Figure 3: SVGF numerical model mesh and layers

Typical values and densities based on gravimetric studies define the general rock properties, grouped in 13 types for the numerical model, three of them corresponding to the geothermal reservoir, as shown in Figure 4. Its distribution tries to replicate the summary of the geoscientific and well-logging data.

The shape of the cap-rock is followed mostly in layers B to D, but it deepens towards the northwest, reaching layer E around SV-1 and layer I by the abandoned SV-3. Below that, since there is evidence of enough permeability for convection regime up to -700 m.a.s.l. (LAGEO, 2020), parts of the reservoir are deepened to layer N and O. The basement is raised to the northeast, as Figure 4 already shows at -425 m.a.s.l., causing the SV-2s to reach it in layer N and deepens to layer Q around the SV-5s in a southwest trend.

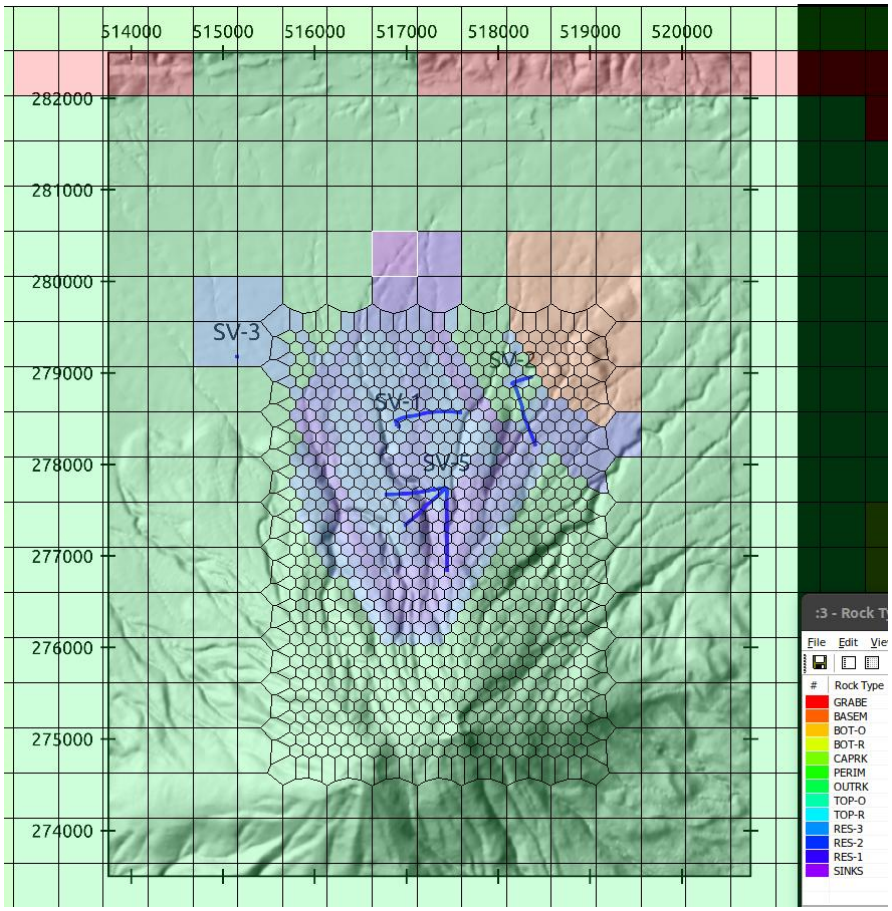


Figure 4: SVGF rock distribution at -425 m.a.s.l.

2.3 Initial and Boundary Conditions

In general, the model starts with temperature and pressure gradients resembling the measured values and water level in the abandoned well SV-3, representing the surroundings of the geothermal system. Five of the rock-types have fixed thermodynamic conditions to provide stable boundary conditions in the perimeter, top and bottom layers. The pressures in the areas above and below the reservoir are calculated from surface averages (LAGEO, 2023a) and extrapolations of the well measurements. Its temperatures are manually assigned trying to emulate the thermal footprint of the fault-dominated main flow, and upflow zone. In the top layer, for the elements corresponding to the two main fumaroles in the field, the surface measured temperatures in its last monitoring are used (LAGEO, 2023b).

2.4 Heat Source and Sinks

The heat source is represented with 10 hexagonal elements in layer R (-1750 m.a.s.l.), at the north-western border of the newer (eastern) crater of the volcano, each of them providing 4.5 kg/s of water at an enthalpy of 1263 kJ/kg, which corresponds to liquid saturation at a temperature of 285°C, in accordance with the calculated geothermometers.

Two of the sinks represent the active fumaroles "Agua Agria" and "Infiernillos Ciegos". The initial simulation-trials confirmed the necessity of an additional natural outflow of the reservoir at depth; hence, a third sink was added to the NNW, in accordance with the conceptual model but proposing a specific location. The confluence of lineaments by gravimetric and by "head-on" resistivity method (LAGEO, 2020) was used at -425 m.a.s.l. for this third sink, highlighted in Figure 4, replicating a typical deepening of the system in the outskirts and aligning with the highest temperature in the nearest well, SV-1A.

Furthermore, a fourth sink at depth was later proposed to the NE, helping to induce the sharp thermal differences between SV-2A and SV-2B, introducing a new outflow route following the next DEM inferred fault parallel to "Infiernillos Ciegos" fault, endorsed by the lack of return of tracer injected in well SV-2B (LAGEO, 2024b), the

alignment of seismic hypocenters at reservoir depths (LAGEO, 2023c) and the re-emergence of the volcanic stratus "Complejo San Vicente" following that trend (LAGEO, 2020).

3 RESULTS

3.1 Permeabilities

The resulting permeabilities for the reservoir volume are around 50-75 mD (millidarcy) within the main faults and well feed-zones, the rest of the reservoir remains around 2.5 mD, and the surrounding rock-type outcome is 0.46 mD. The cap-rock and the basement were kept fixed at 0.01 and 0.001 mD.

3.2 Natural State

The numerical model simulates how the heat source and natural sinks modify the thermodynamic conditions, before any geothermal exploitation, until stable values are reached, typically defined when changes are negligible in a ten-thousand-year period.

The resulting temperatures for the natural state are presented in Figure 5 for a horizontal slice at -375 m.a.s.l., showing its distribution within the reservoir of SVGF. The dashed green line A-A' locates the vertical section of the well-field displayed in Figure 6, which crosses in between the wellheads of SV-1s and SV-5s.

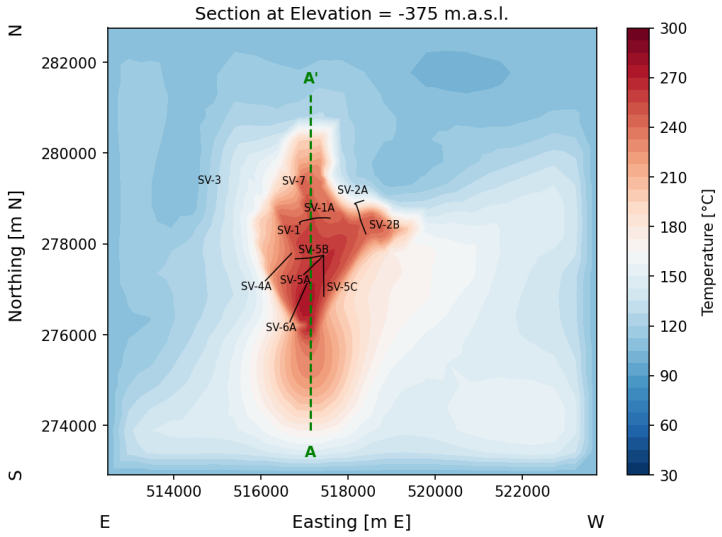


Figure 5: Natural state temperature distribution in SVGF reservoir

It is clear in Figure 6 how the hot fluids flow up from the south and how they irrigate the reservoir area, mainly between -500 and 0 m.a.s.l., in accordance with the conceptual model of the geothermal system and the evidence of well feed-zones in this range of depths (LAGEO, 2020).

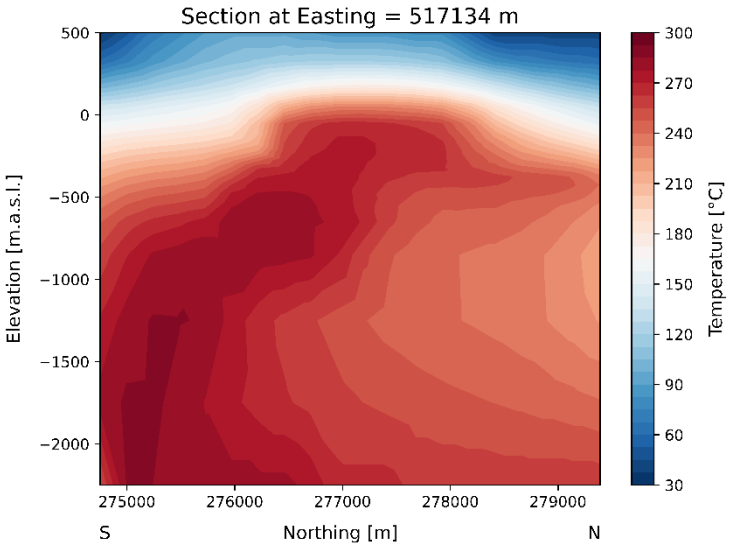


Figure 6: A-A' vertical section with modeled temperatures of natural state of SVGF.

To evaluate the natural state fit, the temperatures of elements along the actual well-tracks are compared to selected static temperature measurements with better thermal recoveries to represent the undisturbed formation conditions. A general good correlation was achieved, Figure 7, quantified in a 91.8% coefficient of determination (R^2).

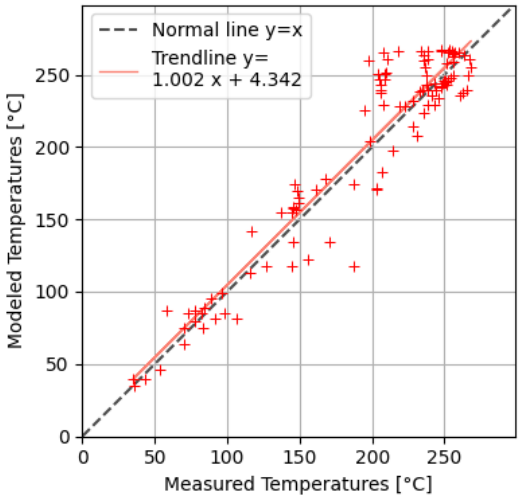


Figure 7: SVGF natural state temperature dispersion along well-tracks

As seen in Figure 8, the thermal regression towards the bottom of the wells has been successfully replicated, especially in the deepest well SV-1A, but the modeled temperatures are slightly higher than expected. The maximum temperatures in the producer wells, SV-5s, tend to be in shallower depths than the measurements due to the higher permeabilities around the concurrent feed zones around -50 m.a.s.l., enabling the geothermal hot irrigation. The drastic temperature difference between the SV-2s wells was successfully replicated, but SV-2B is overly heated around its deepest feed zone (-250 m.a.s.l.). The surroundings of the reservoir maintain a good fit, evaluated in the abandoned well SV-3.

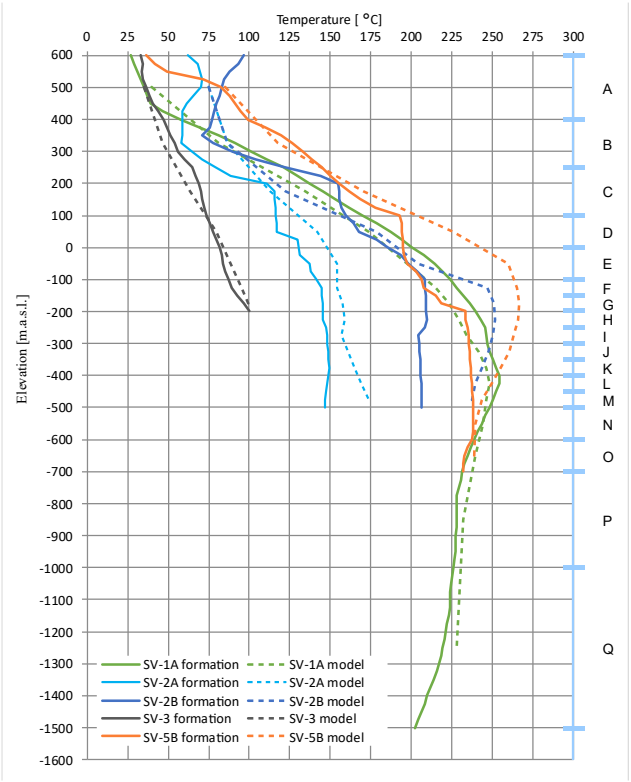


Figure 8: SVGF natural state temperature profiles

Since the depth and pressure at the pivot point are the best indicators of formation pressure for multiple-feed wells (Grant and Bixley, 2011), the pressure comparison, gathered in Table 1, is focused on the elements coinciding with each of them. The results show that the model natural state pressures are around 6.8 bar higher than expected. Presumably the natural outflow of the reservoir needs to be increased, either with additional sinks or better connections to the present ones.

Table 1. Natural state formation vs modeled pressures in well pivot-points of SVGF.

Well	Elevation [m.a.s.l.]	Formation pressure [bar-a]	Modeled pressure [bar-a]
SV-1	-425	73.8	78.0
SV-1A	-550	79.8	82.2
SV-2A	-50	34.9	40.7
SV-2B	-275	56.4	61.4
SV-3	N/A	N/A	N/A
SV-5A	-375	61.6	76.8
SV-5B	-50	42.1	51.5
SV-5C	-50	42.9	51.7

3.3 Production Stage

The main calibration variable during the production stage is the reservoir pressure which is continuously monitored in well SV-1A at 1000 m MD (-150 m.a.s.l.) and the starting pressure of reference is established from a previous static PT-log, because of irregularities in the initial records due to leakage in the pressure chamber.

The calculated pressure drawdown and fluid enthalpies comparison is shown in Figure 9, with a general good match with the numerical model. The main differences appear with the start of production with the second well, SV-5B, where the model expected a more pronounced impact in the monitored pressure in well SV-1A.

The flow distribution between the SV-5B feed-zones will be reviewed since it is based on PTS measurements during injection into the well and not under producing conditions.

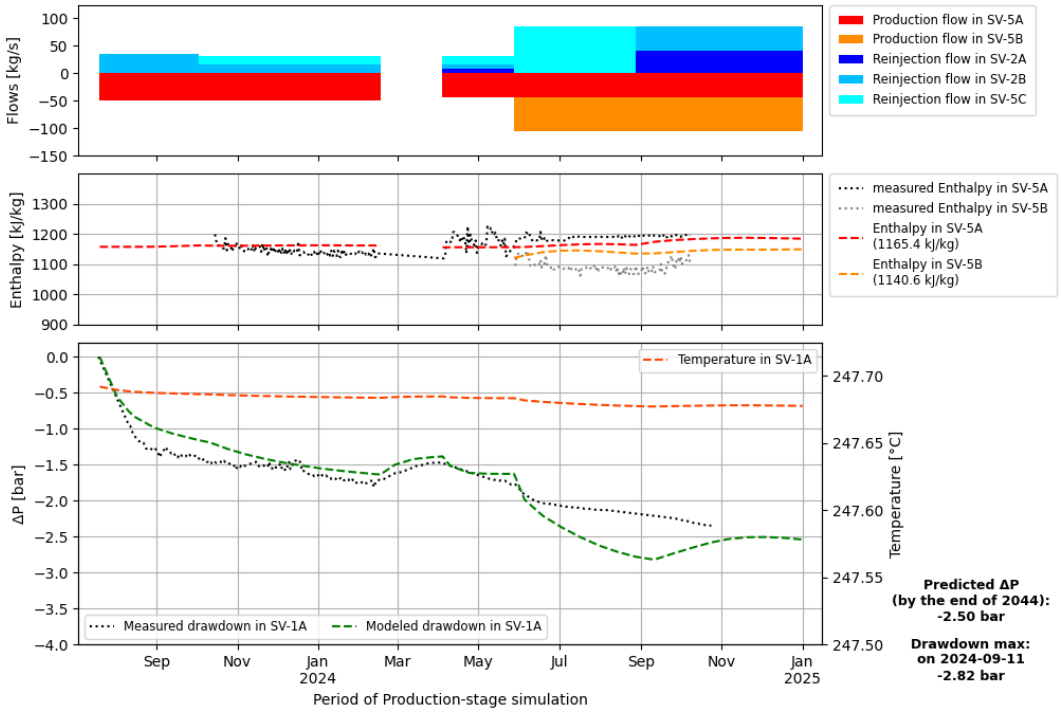


Figure 9: Modeled and measured enthalpies and pressure drawdown in SVGF.

The annual monitoring of the fumaroles will be important to determine how their evolution is affected by the extraction and reinjection of geothermal fluid, specially “Infiernillos Ciegos” fumarole due to the closeness to reinjection well SV-2B, improving the indexes used in the numerical model.

3.4 Future forecast

Several operation scenarios were simulated for the next 20 years on request for field management, but it is crucial to highlight that the predictions from numerical models are valid, in general, up to a similar period to the production history to which it was matched (Grant & Bixley, 2011). In this case the first 15 months of production were utilized therefore the prognosis should be considered only as a preliminary approximation to the possible upcoming evolution of SVGF and the examples in the following sections will be limited to a 5-year period in the future to show a production expansion comparison.

3.4.1 Operation scenario #2: keeping present configuration

Under this configuration, the producing wells SV-5A and SV-5B maintain the present rates of extraction, reinjecting all the brine evenly in SV-2A and SV-2B. Since the extraction does not decline with time, the pressure drawdown shown in Figure 10 should be a pessimistic range.

The simulation results in a slowly diminishing pressure decline of -6.4 bar by the end of 2028 with a probable trend of slow stabilization in the future. The enthalpies of both producing wells have small changes in the simulated period, as well as the temperature in the formation around the monitoring well, SV-1A, feed-zone. These results suggest that the SVGF geothermal capacity is enough to sustain the current operation rate over a prolonged time but should be reassured in the future when the model is updated with more production history.

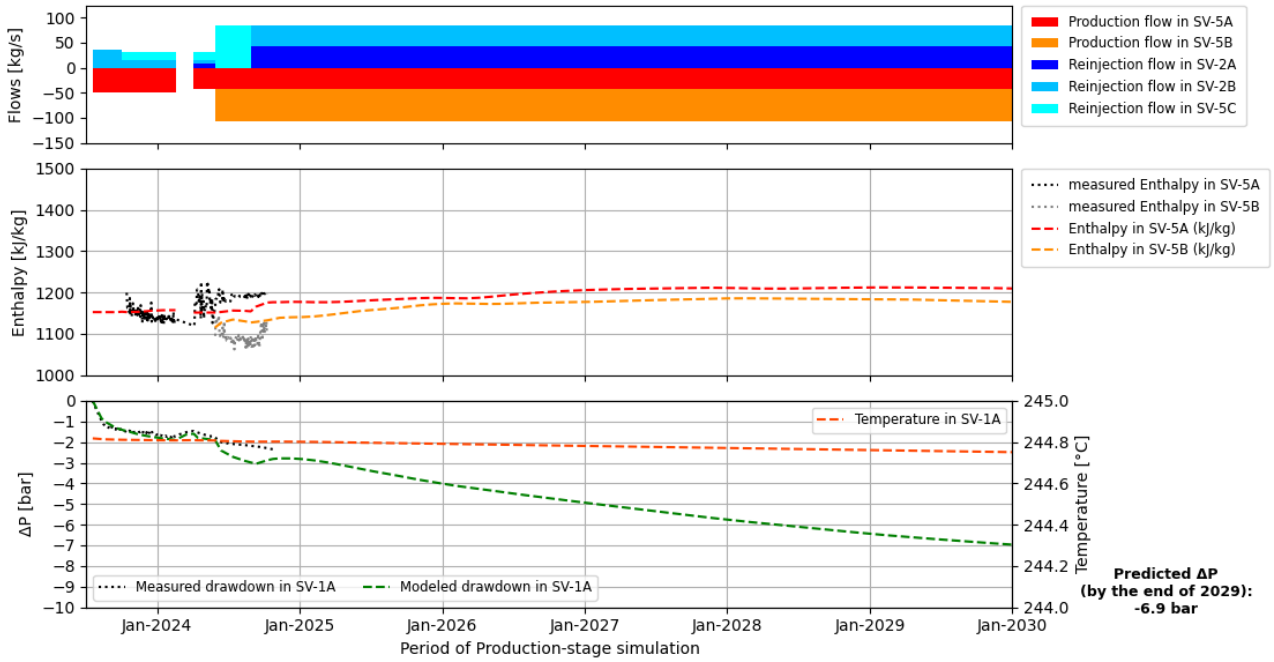


Figure 10: SVGF scenario #2 forecast

3.4.2 Operation scenario #5: adding three production wells and single-flash condensing units

The more exhaustive scenario relies in a successful stimulation and stable production from the existing well SV-5C from year 2026 onwards, and from wells SV-6A in 2027 and SV-4A in 2028, both yet to be drilled but with existing well-pads and planned objectives (LAGEO, 2021a&b). For each producer well a fixed extraction of 50 kg/s of geothermal fluid is assigned which adds 10 kg/s of steam (at a typical quality of 20%), totalizing 51.2 kg/s of steam in the 5 producer wells. With a typical conversion efficiency for flash units of 2 MWe for each kg/s of steam, around 25.6 MWe could be produced in this scenario.

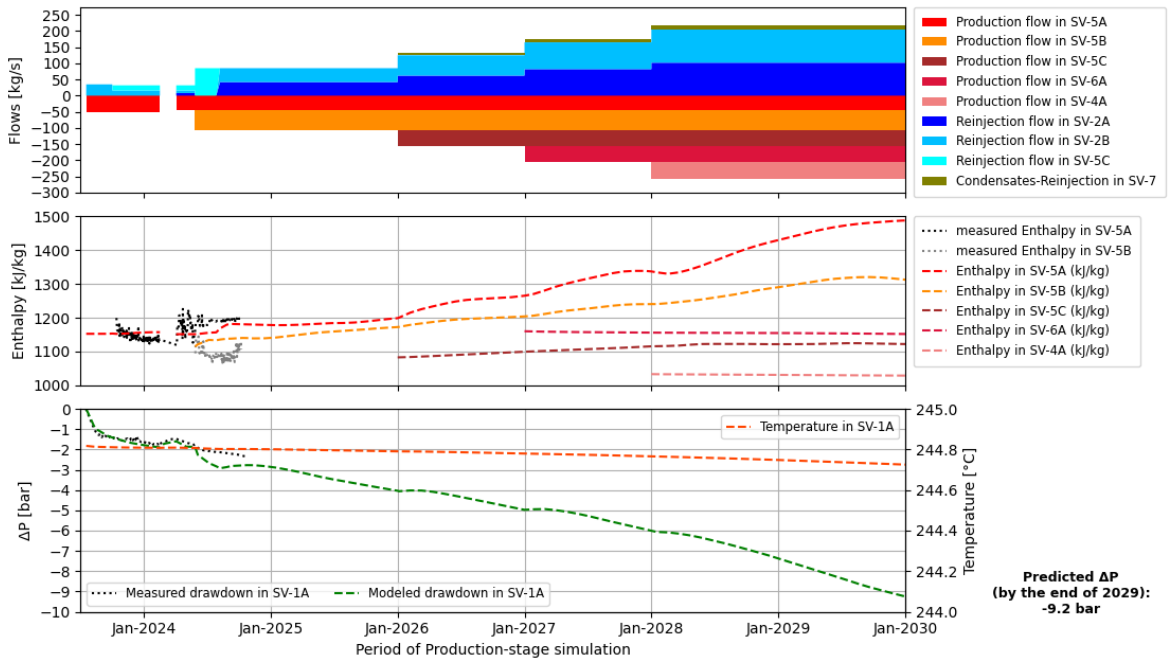


Figure 11: SVGF scenario #5 forecast

The resulting pressure drawdown is clearly more drastic, decreasing -9.2 bar by the end of 2029, with clear decline accelerations with each new producing well. The enthalpies of wells SV-5A and SV-5B increase up to

around 1500 and 1300 kJ/kg, since their extraction flows are fixed in the model, the future additional producer wells show an impact in their steam fraction but must be further analyzed in future evaluations to regard changes in their flows. The effect on the temperature in the formation around the monitoring well SV-1A feed-zone increases from -0.2 °C only to -0.5°C, therefore no drawbacks of reinjection cold front are predicted yet, but it can be further reviewed in the next updates of the numerical model.

Although the pressure decline is a less steep initial depressurization than in the other two geothermal fields under exploitation in the country, Ahuachapán and Berlin (Rodríguez and Monterrosa, 2007), the producing wells show thermodynamic changes that prompts to reassess the field evolution with each new drilling, which allows further well-testing and adjust the geoscientific research.

4 CONCLUSIONS

The numerical model of SVGF presented in this paper (with its pre- and post-processors scripts) successfully provides a more robust working framework than its predecessors and serves as a valuable input for field management, especially due to its capacity for forecasting scenarios with growing credibility as more production and field monitoring data is available for its adjustment.

The natural state and production history fitting achieved is adequate but suggests that the natural outflow of the reservoir needs to be further evaluated, monitoring the surface manifestations and updating the geoscientific research. Especially with the proposal of a new exit route for the geothermal fluids in this numerical model, which could lead to new objectives for future reinjection wells in the eastern area, if confirmed.

Although the forecasting period requires more production history to increase its credibility, the pressure drawdowns are less pessimistic than its predecessor, confirming that the current operation can be sustained but suggesting that the future expansion and conversion to condensing units should be stepwise to evaluate the interference between the proposed producer wells and refine the field potential calculations. The upcoming update of this numerical model, already underway, includes a volumetric resource estimation based on the resulting permeable blocks from the simulation.

Specifically, the SW border of the reservoir will be enlightened with the next producer well-drilling, since the current prediction appears to have an even sharper temperature regression towards the bottom unless the border is expanded, which will be crucial for the volume calculations and to adjust the drilling objectives approaching the upflow zone.

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