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A New Numerical Model of Amatitlán Geothermal System, Guatemala

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ABSTRACT

The Amatitlan geothermal field has a high-temperature reservoir, with feedzone temperatures in most of the production wells reflecting boiling conditions. The existence of a shallow vapor-mobile two-phase region (i.e., a "steam cap") and a deeper extensive two-phase reservoir were confirmed by two wells (AMF7 and AMF8). Gas concentrations are variable but modest calcite scaling exists in AMF1RD. Temperature distribution suggests that the upflow of the Amatitlán geothermal system takes place beneath a significant area of the active Pacaya volcano. The revised conceptual model suggests that the outflow of the system flows laterally toward Lake Amatitlán. A three-dimensional numerical model consisting of 11,240 grid blocks was developed for reservoir simulations. Natural-state and production/injection simulations for near 12 years of exploitation were conducted using this model and AUTOUGH2 simulator, TIM pre-and post-processor and Py-TOUGH scripts. TIM and Py-TOUGH were essential for optimizing the model block structure, adding meteoric recharge and background heat into the model, assigning the topography to the top surface of the model and to represent Lake Amatitlán, all required for dealing with the complexity of the real geothermal system. Simulated temperatures and pressures distribution in natural state match field data measured prior exploitation. For production history matching a dual porosity model was developed and it reproduces current flow rates and enthalpy of produced fluid by the production wells. The model also reproduces pressure transient data of one monitoring well (AMF7). The effects of calcite scaling on production parameters of well AMF1RD is addressed in the model mainly by using the new generator type DELT, Yeh, A., et. al (2012). The model is capable now for predictions. As an example, a base case scenario was run; this base case scenario was divided into two different cases: Scenario one considers continue production as it is now for the next fifteen years without taking into account scale in the best production well AMF1RD. The second scenario is the same case as scenario one but it takes into account scale in wellbore and formation of AMF1RD. Results of simulated prediction scenarios are that by considering the scale issue during the simulation study, the simulated MW thermal are more realistic that the case that doesn't consider scale. The difference in terms of MW thermal for both scenarios is about 2% lower for the most realistic case. Simulations also show a decline on MW thermal for both cases of about 0.90 MW thermal per year.

1. INTRODUCTION

The Amatitlán geothermal field is located 40 kilometers southwest of Guatemala City, on the north slope of Pacaya volcano, covering an area of roughly 12 km^2. (Figure 1). The geothermal resource was originally explored and developed by INDE. Ortitlan began operating the wellfield and an ORMAT combined cycle power plant was commissioned in February 2007. To date, nine wells have been drilled during five drilling campaigns (1993, 2000, 2006, 2009 and 2013), with well's depths varying from 805 meters to 2058 meters, and two of those wells being directionally-drilled (AMF6 and AMF7) (Figure 2). Geochemical data indicates that the system is fed by a deep 330°C fluid that cools adiabatically by boiling so that the deep reservoir has a temperature of 280-300°C. This is a high temperature reservoir with feedzone temperatures in most of the production wells reflecting boiling conditions. The existence of a shallow steam cap was confirmed by two wells. Gas concentrations are variable but modest and calcite scaling is only observed in AMF1RD, which encountered high permeability feed zones at two different depths. WestJec developed a numerical model of Amatitlán in 2002 that was later updated in 2004, 2008 and 2009, WestJEC (2002), WestJEC (2008), WestJEC (2009). In 2014, Geothermex, submitted a report, Geothermex (2014), that included an estimation of the recoverable reserve using Monte Carlo Simulations. The primary objective of the present work is to develop an updated numerical model of the Amatitlán geothermal field that can be used to predict the future behavior of production wells, the effects of injection and the overall depletion of the geothermal reservoir. The model is three-dimensional and well-by-well, which allows for history matching flow rate and enthalpy data from all wells and pressure draw down in the reservoir. The present model is capable to predict future mass production decline of the existing wells, generation capacity, effects of injection on well's behaviors, effects of calcite scaling, and it uses state-of-the-art techniques on three dimensional simulations of geothermal systems.

2. FIELD DEVELOPMENT

The development of the Amatitlán geothermal field started in the 1970's. In the 1980's INDE drilled nine slim temperature gradient holes (AM1 to AM9). Two more slim holes (AM10 and AM11) were drilled by INDE between 1989 and 1992. From 1992 to 1993, four exploratory commercial wells (AMF1 to AMF4) were drilled and in 1994 production tests were conducted. Wells AMF1 and AMF2 succeeded in tapping the geothermal reservoir. From 1998 to 2000 wells AMF5 and AMF6 were drilled and both wells found commercial permeability and temperatures. A feasibility study conducted by WestJec concluded that a power plant could be fed with steam produced by wells AMF1, AMF2, AMF5 and AMF6 and injection could take place in wells AMF3 and AMF4 (Figure 2). INDE operated a 5 MW back pressure unit powered by AMF1 and AMF2 from 1998 to 2006, with injection into AMF3.

In 2002, ORMAT obtained the concession for the geothermal development of Amatitlán. In 2006, ORMAT drilled well AMF7 as a backup well for steam production. Although some steam was obtained, the well did not tap into the expected production zone. The Ortitlan power plant officially came online in August 2007; wells AMF1, AMF2, AMF5 and AMF6 were producing geothermal fluid for feeding the plant and wells AMF3 and AMF4 were injecting all the produced fluid. In 2008, WestJec updated the 2002 numerical model of Amatitlán. Testing data and first few months of flowrate history were used for the model calibration. This updated model was used for evaluating new drilling targets. In 2009 ORMAT drilled well AMF8. This new well tapped a shallow dry steam cap and succeeded in supplying additional steam to the power plant.

In 2013, well AMF1 was plugged and abandoned (P&A) and new well AMF1RD replaced it. This new well was completed with bigger casing and liner, as well as better drilling technique was applied when drilling the production zone for avoiding damages of the formation. This is the reason why AMF1RD became a success and the best production well in Amatitlán, since being put online, AMF1RD has experienced calcite scaling issues that have been deal with all available and newest technologies. AMF7RD was drilled in 2018 finding permeability that is not commercial.

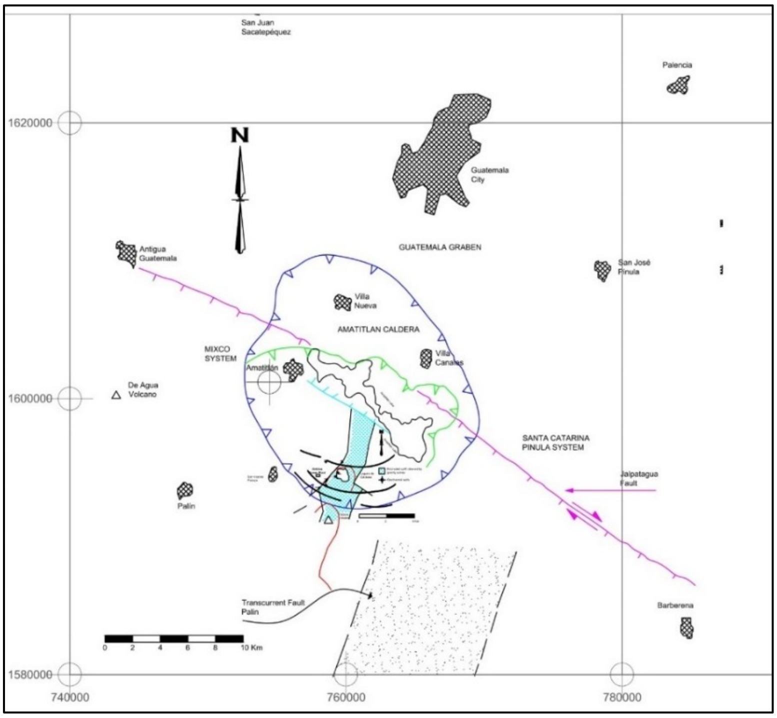

Figure 1: Geological structure of the Amatitlán geothermal field, Modified from Eggers, A. (1972).

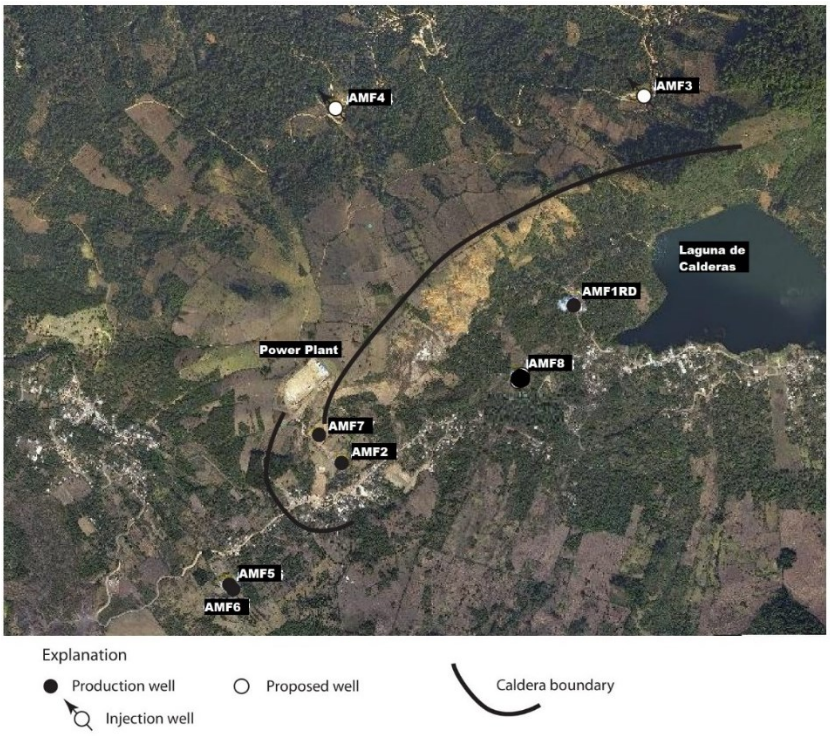

Figure 2: Location of wells drilled in Amatitlán.

3. GEOLOGICAL SETTING

The stratigraphy of the geothermal system of Amatitlán can be deduced from information provided by the existing wells. WestJec and Geothermex reported and agreed on the following time-stratigraphic units:

- Pacaya volcanics: basalt and brown tuff erupted from the Pacaya volcano
- Post-Caldera volcanic rocks: andesites, tuffs and tuff-breccias erupted since the collapse of the Amatitlán caldera
- Syn-caldera volcanic rocks: andesite, tuff and tuff breccia erupted contemporaneously with caldera collapse
- Pre-caldera volcanic rocks: volcanic products similar to the syn-caldera volcanic rocks but erupted prior to the caldera collapse
- Basement rocks: granite porphyry and dikes of diabase and dacite

Basement granite rocks have been encountered in wells AMF1, AMF4 and AMF5 at vertical depths >1600 m. The top of the basement at the eastern side of the depression can be found at about +500 m msl compared to +230 m msl in AMF5 located on the west. The permeable zones associated with production occur primarily in the volcanic units above the basement. The main production zones in the wells drilled in the Laguna de Calderas depression are all located within the Pre-Caldera stratigraphic unit (+600 to +400 m msl). The permeable zones found in most of the production wells could be related to fracturing on one or more of several faults thought to exist in the Laguna de Calderas depression; from these faults, the caldera rim fault bounding the depression on the NW (Figure 3) has the most prominent topographic expression.

4. CONCEPTUAL RESERVOIR MODEL

Figure 3 shows a plan view of the conceptualized system and Figure 4 shows a cross-section of the conceptual model that has been developed for the Amatitlán Geothermal System, modified from WestJEC (2009). The main elements of the conceptual model are listed below:

The geothermal system area is mainly controlled by a caldera structure (Figure 4), a 1.5-2 km-wide N-S oriented basement horst structure and a dacitic intrusion. Figure 4 shows a conceptual N-S cross section of the Amatitlán geothermal field. At the fractured zone formed by the west edge of the basement uplift zone, the Na-Cl high temperature reservoir fluid is confined to the zone from the granitic basement of about 2,000 m in depth to the lower Tertiary volcanic rocks. This type of fluid is a mixture of the meteoric water percolating to the deep underground and magmatic water as suggested by stable isotope compositions Lima, E., et. al (1996) supplied from the magma reservoir at the deeper zone. This parent water reaches 300°C to 340°C and probably is the parent fluid for the whole geothermal system in the Amatitlán area. At 500 m (msl) above the west edge of granite basement, the geothermal fluid reaches 290-300°C in temperature and 2,700 mg/l in Cl content. It is derived from the deep parent fluid that is contained within the fracture zone associated with faults. The boiling fluids traveling through the NE-SW horst boundary manifest at the surface as fumaroles and are responsible for the altered zones exposed on the west-wall of the Laguna Caldera. Hot boiled fluids migrate northward towards well AMF1RD, forming a water-dominated reservoir with a low enthalpy and high salinity. Boiling accompanied with the rising of geothermal fluids leads to silica deposition and an argillic alteration zone in the shallow parts of the systems creates a cap-rock for the reservoir. This "clay cap" is visualized in MT inversion models as a low resistivity anomaly. In the area beneath and surrounding wells AMF1, AMF2, AMF7 and AMF8, steam and liquid co-exist forming a two-phase reservoir just below this cap-rock. Because of the extent of this anomaly, it is concluded that the reservoir may extend towards the north, following the path of the band-shape low resistivity anomaly. According to the geochemical analysis, hot water is gradually diluted by meteoric water, causing the temperature to decrease along its travel towards Lago de Amatitlán and forming the hot spring aquifer. At the northeastern part of the Amatitlán area, relatively low temperatures have been recorded at elevations between 0-500 m. This may suggest that the Lago de Amatitlán water may be percolating towards the southwest as seen in the temperature reversal recorded at well AMF3. The temperature reversal in well AMF3 could be also explained as the result of shallow high temperature outflow to the north. The high temperature geothermal reservoir, 290°C to 300°C, may exist at 200m elevation and extend widely around the dacitic intrusion inside Laguna Caldera. In addition, it is anticipated that a parent geothermal fluid of 300°C to 340°C, not yet confirmed, exists in the deep zone.

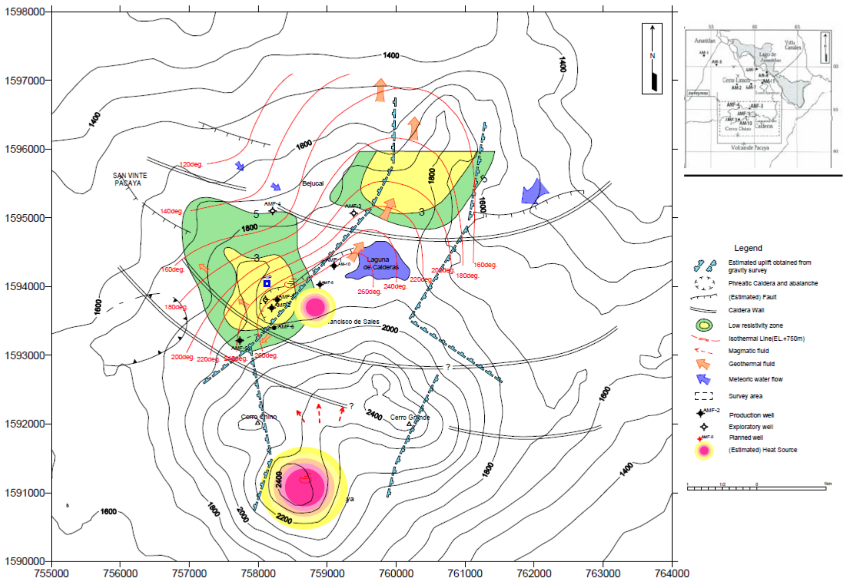

Figure 3: Conceptual model of the Amatitlán geothermal system (Plan View). Modified from WestJEC, (2009).

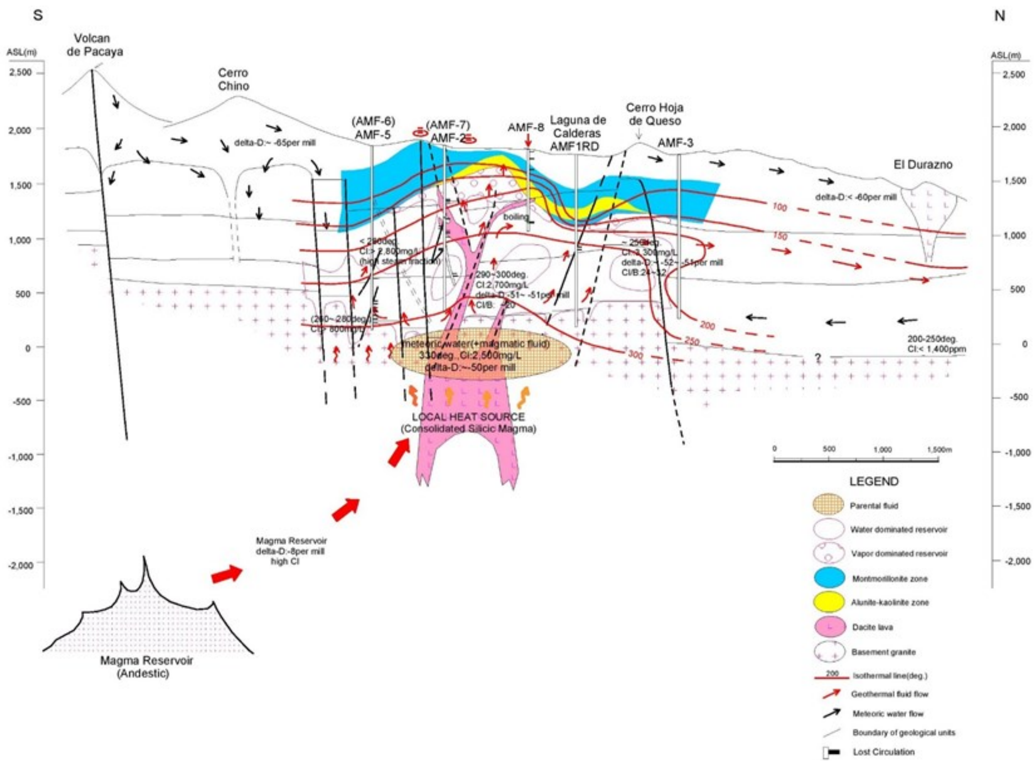

Figure 4: Cross Section S-N. Conceptual model of the Amatitlán geothermal system. Modified from WestJEC, (2009).

5. NUMERICAL MODEL

The extent of the model was designed to encapsulate the Amatitlán Lake, the Pacaya Volcano Complex, the Amatitlán Caldera and all the geology structures imbedded in the complex geothermal area (Figure 5). The mesh axes are oriented in parallel to the main faults that trends N-S and WNW-ESE.

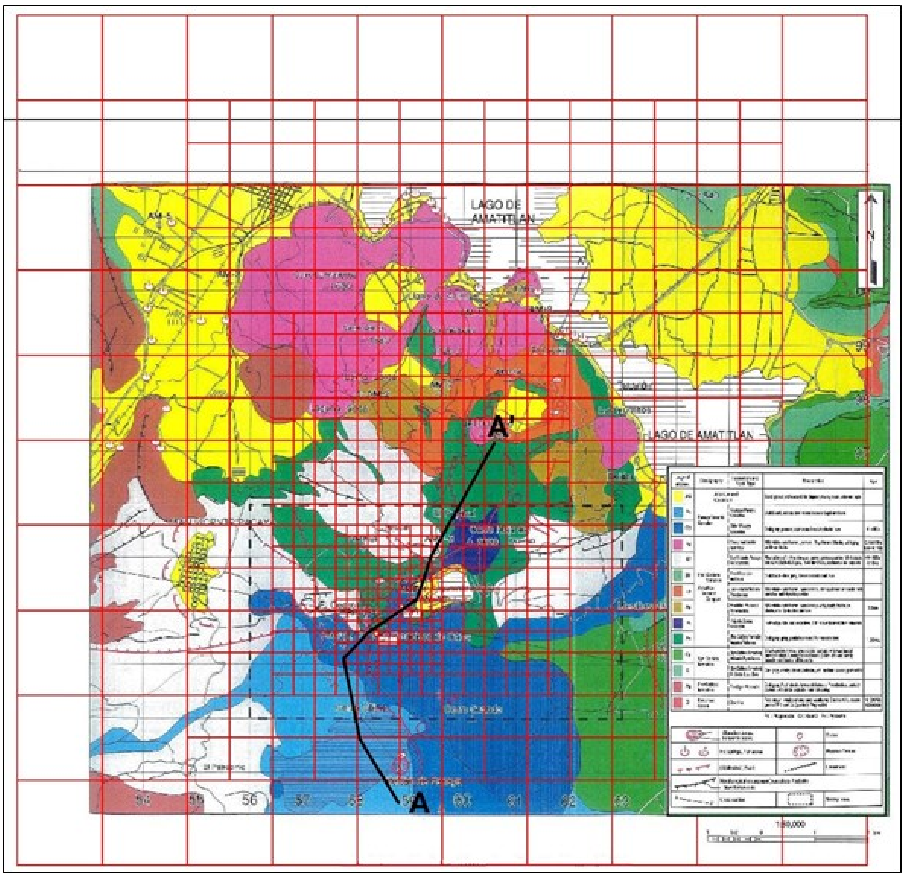

Figure 5: Surface geology (adapted from Eggers, A., 1970) and model grid overlaying. Cross section A-A' is shown.

The model center has the following coordinates WGS84 zone 15 UTM Easting 75960 Northing 1597600. This grid system obeys for a criterion based on location of the main faults that allows the circulation of fluid as well as to locate each active well in a different grid. The criteria of one well per grid will allow us to avoid any extreme pressure drop due to high production rate from one specific grid. Figure 5 shows the plain view of grid system projected on a topographic map of the Amatitlán area. Figure 6 represents the enlarged area where the exploitation area is located. A square area of 16 km by 16 km was selected for grid system of numerical model with 5.4 km depth. The model consists of 11,240 grid blocks in a size range from 200 m x 200 m in the central part of the model (production area) to 1,600 m x 1,600 m at the outer part of the model. In a vertical direction, the model was divided into thirty-six layers with different thickness for a total thickness of 5400 m, from 2,400 m above sea level to 3,000 m below sea level. A very fine vertical resolution of 20 m layers was assigned in the elevation range where the water table is located. The numerical grid was optimized with a Py-TOUGH routine, Croucher (2012) that ensures block faces are perpendicular to connections between block centers. Topographical and bathymetric data were used to allocate appropriate surface elevations to each column in the grid. Various new software tools were developed and used for the construction, calibration and analysis of the model. Many of these are based on Py-TOUGH scripts. They are used for block optimization, assignment of background heat, rainfall, infiltration rate, and surface fitting. As for pre-and post-processor for building grid system a Graphical User Interface called TIM, Yeh, A., et al. (2013) was used. Figure 7 shows the cross section of the model with layers and their thickness. The location of the main feed zones for all the wells in Amatitlán is also plotted with different symbols. Table 1 summarizes the depths of bottom and top of layer as well as the depth of centers and thickness of each of the thirty-six layers in the model.

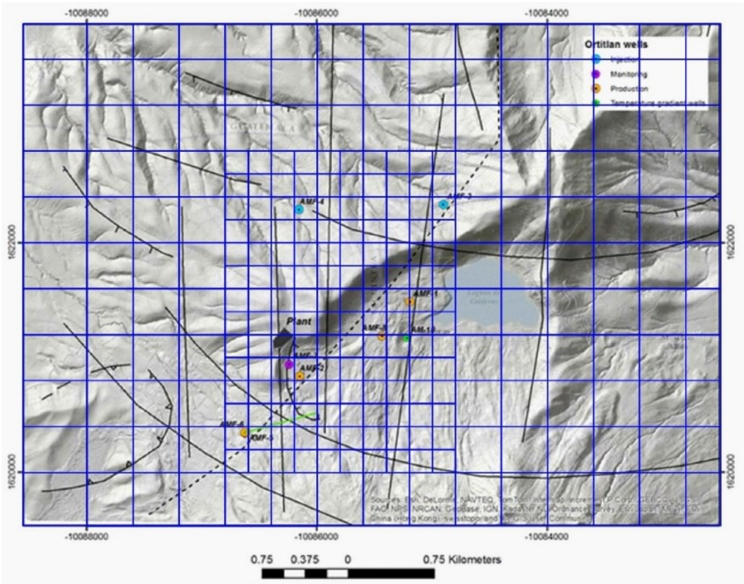

Figure 6: Enlarge production area where the wells are located into the numerical grid.

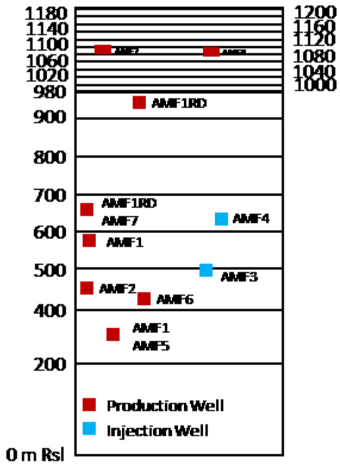

Figure 7: Layers of the model and location of main feed zones of Amatitlán wells.

Closed lateral boundary conditions were used, as the model extent was designed to encompass the Amatitlán Lake, the Pacaya Volcano Complex, the Amatitlán Caldera and all the geology structures imbedded in the complex geothermal area. At the top of the model "Atmosphere Blocks" were assigned as top boundary to represent atmospheric conditions at the subsurface. These atmosphere blocks are set to be sufficiently large, so their temperature and pressure do not change in time during the course of simulations, despite their interaction with the surface blocks, O'Sullivan, M. J., et. al. (2009). Two types of Atmosphere Blocks were used in the model: one for dry land and the highlands and the other to represent the influence of Amatitlán Lake. The distribution of the two types of surface boundary conditions used for the Natural State simulation is shown in Figure 8(a) and Figure 8(b) shows the distribution blocks at the bottom layer assigned to the up-flow where mass was injected to the model.

Table 1: Center of grid nodes and thickness.

Layer name	*Elevation (m)*	*Thickness (m)*	*Elevation of grid center nodes*	*Layer name*	*Elevation (m)*	*Thickness (m)*	*Elevation of grid center nodes*	*Layer name*	*Elevation (m)*	*Thickness (m)*	*Elevation of grid center nodes*
1	2300 to 2400	100	2350	13	1180 to 1200	20	1190	25	800 to 900	100	850
2	2200 to 2300	100	2250	14	1160 to 1180	20	1170	26	700 to 800	100	750
3	2100 to 2200	100	1150	15	1140 to 1160	20	1150	27	600 to 700	100	650
4	2000 to 2100	100	2050	16	1120 to 1140	20	1130	28	500 to 600	100	550
5	1900 to 2000	100	1950	17	1100 to 1120	20	1110	29	400 to 500	100	450
6	1800 to 1900	100	1850	18	1080 to 1100	20	1090	30	200 to 400	200	300
7	1700 to 1800	100	1750	19	1060 to 1080	20	1070	31	0 to 200	200	100
8	1600 to 1700	100	1650	20	1040 to 1060	20	1050	32	-200 to 0	200	-100
9	1500 to 1600	100	1550	21	1020 to 1040	20	1030	33	-500 to -200	300	-350
10	1400 to 1500	100	1450	22	1000 to 1020	20	1010	34	-1000 to -500	500	-750
11	1300 to 1400	100	1350	23	980 to 1000	20	990	35	-2000 to -1000	1000	-1500
12	1200 to 1300	100	1250	24	900 to 980	80	940	36	-3000 to -2000	1000	-2500

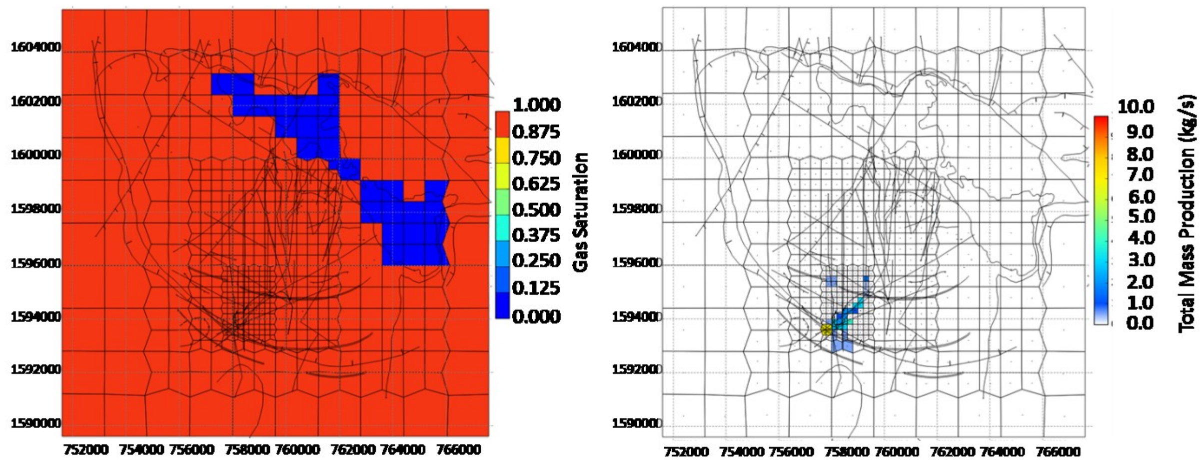

Figure 8: Boundary conditions. (a) Surface model blocks of the system with a dry atmosphere in red and wet atmosphere in blue (blocks representing Lake Amatitlán). (b) Upflow at the base of the best-fit model.

6. MODEL CALIBRATION

The simulated results for natural state were compared with measured water table levels, flowrates discharged to the atmosphere through surface manifestations, temperature and pressure profiles of the six big hole wells as well as existing slim-hole wells. This matching procedure was conducted mainly by adjusting permeability of rock types, flow rate and enthalpy of recharge assigned at the bottom grids. The natural state model was run until a steady state was achieve. These modifications need a lot of computing time and tedious work on input data.

6.1 Measured and calculated water table levels

In the conceptual model the high elevation areas around Pacaya Volcano, Cerro Chino, the volcanic complex to the south and Lake Amatitlán (Figure 4) are important meteoric recharge areas for the geothermal system. Some of this meteoric recharge infiltrates deep into the subsurface through the structures and joins the convective plume. The hydrothermal fluid floats by buoyancy in a northerly direction until it reaches the shores of Amatitlán Lake. In general, the permeabilities used in the shallow formations of the best-fit model are much larger than those found in the deeper formations. This is because of the lower compressive forces and less compaction at shallower depth. The much higher fluxes of water in the shallow sub-surface also leads to higher rates of subsurface weathering which increases local permeabilities. There is a feedback in this process; the increase in permeabilities allow even higher water fluxes, and this effect can create high permeabilities in the shallow subsurface, Phillips (2005).

The most important formation for controlling the position of the water table was the Colluvium and Alluvial and Pacaya volcanic rocks as it occupies much of the low-lying areas around the Amatitlán Lake. In the best-fit model the permeabilities obtained for the rock types in this group lie within the range of 5 x 10^{-11} m^2 to 5 x 10^{-13} m^2.

Figures 9(a) and (b) shows plots of the best-fit model result for gas saturation on vertical slices through the main geothermal area of Amatitlán. The real topography is indicated on each slice with a black line and the measured and interpreted bottom depth of the two-phase layer with a blue line. It can be seen in both slices that despite the use of small model blocks in this region (100 m x 400 m x 400 m) some of the complex topography has been smoothed out in the discretization process. The plots of gas saturation show that the model captures the unsaturated zones above the water table. The shallow boiling zone is clearly apparent in both slices and in some columns, it extends to the surface. This is consistent with the behavior of the real system where steaming ground, fumaroles and hot springs occur in many parts of the main geothermal area.

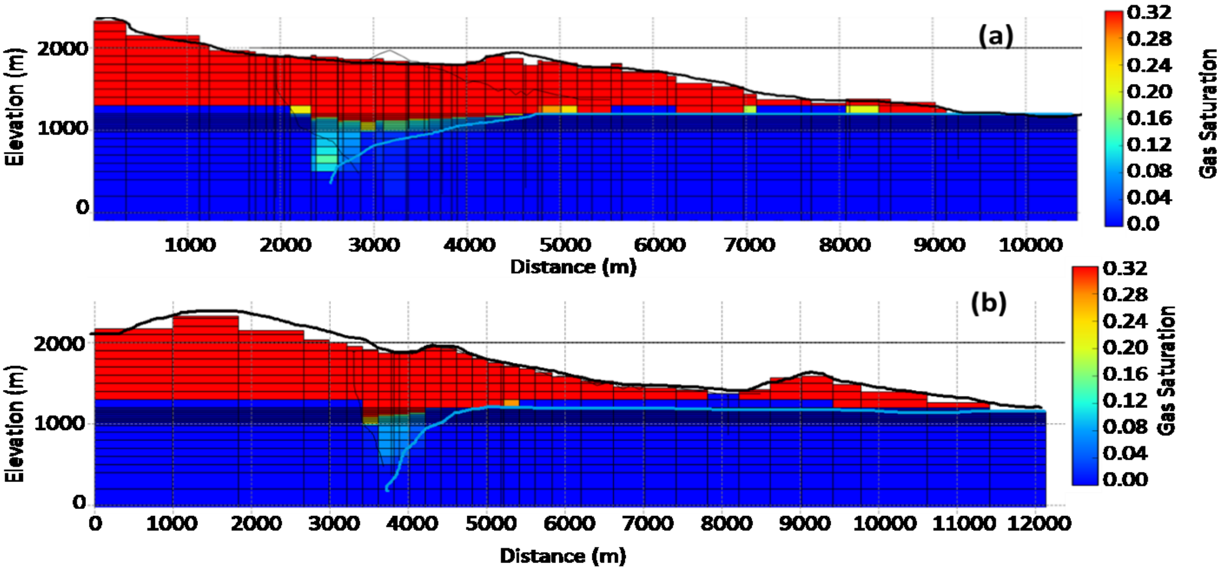

Figure 9: Vertical Cross Section across the center of the wellfield of simulated gas saturation.

The good match between the model results and the measured and interpreted water table levels shows that the model represents well the shallow formations at Amatitlán.

6.2 Temperature and Pressure Profiles in Natural State

The main objective of the natural state calibration is to match the temperature and pressure distributions and the heat/mass flow aspects of the model. In this context, the major rock properties of importance are permeability and thermal conductivity. After many runs of the model a best fit model was obtained when comparing downhole temperatures and pressure. Figure 10 below shows comparison between some of the best measured and simulated pressures and temperature profiles for all the wells used during calibration.

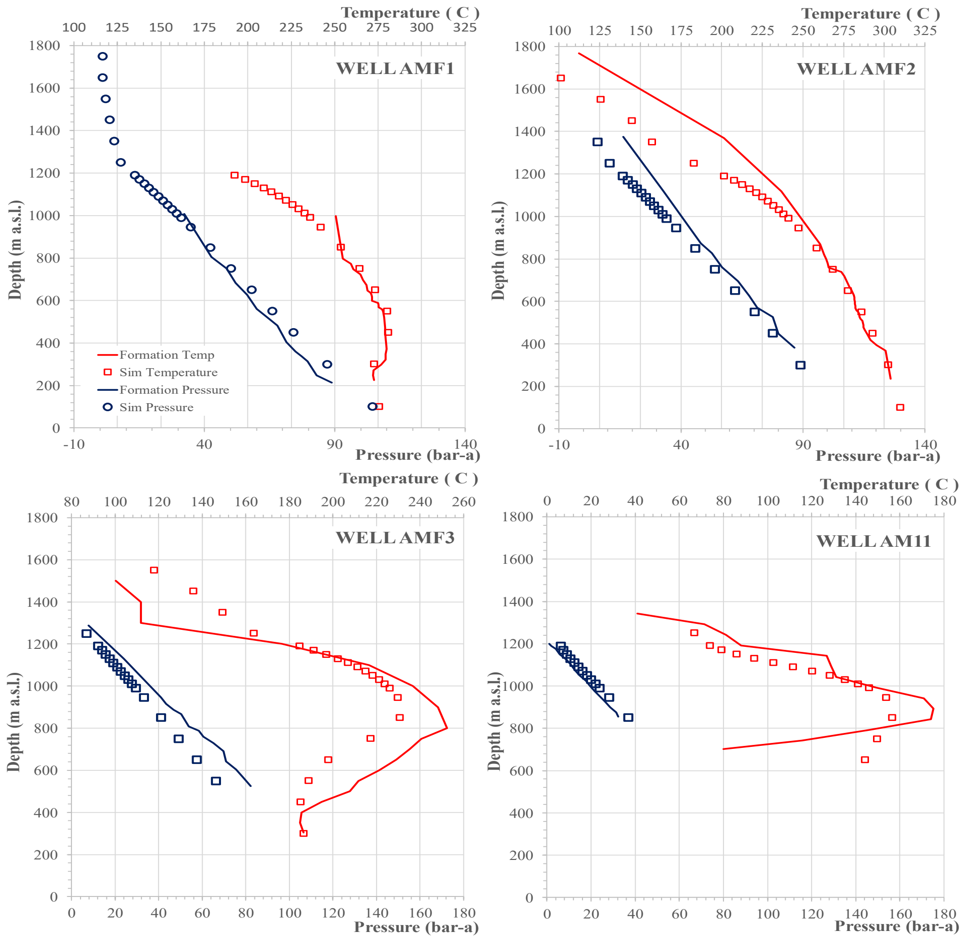

Figure 10: Initial and simulated temperature and pressure profiles of selected wells.

Measured downhole pressures and temperatures of wells AMF1, AMF2, AMF3, AMF4, AMF5 and AMF6 have a good agreement with simulated values. From the measured down-hole temperatures it can be seen that wells AMF2, AMF5 and AMF6 are near the deep up-flow as the temperatures in these wells are the highest recorded by well-logging at over 300°C. In the conceptual model this up-flow is thought to occur at the south-western part of Laguna Calderas. The higher temperatures are related to a small-scale caldera, west of Laguna Calderas, and there are also several fumaroles on the surface that can be related to this up-flow. For the case of the wells, a good match of temperature and pressure was achieved.

For well AMF3 the temperature reversal at 500 masl was reproduced by the model. This temperature reversal extends towards north for several kilometers until it reaches the south shore of Amatitlán Lake as shown in the conceptual model. This well is in the outflow zone of the system. For well AMF4, a slight anomaly of a relative low temperature reversal at 600 masl that extends in the ESE direction was reproduced by the model when allowing cold water to infiltrate into the inner-most caldera rim. This lateral flow extends in the ESE direction.

In the conceptual model it is proposed that beneath and surrounding the area of wells AMF1, AMF2, AMF7 and AMF8, steam and liquid co-exist forming a two-phase reservoir just below the cap rock. The model reproduces this two-phase zone and it extends towards the north following the path of the band-shape low resistivity anomaly related to the uplift granite basement. A good match of temperature and pressure profile was achieved for well AMF1, AMF7 and AMF8.

A mismatch between measured and simulated downhole pressure and temperatures in the slim-holes is a consequence of the large model grid blocks in the region where these wells are located (AM1, AM5 and AM8) that do not provide sufficient resolution to capture the complex temperature and pressure distribution occurring nearby. The cold inversion in the shallower regions of the system is difficult to achieve in the model and this is out of the scope of this study. Despite of the limitation in resolution of the model, the matching is good. In conclusion, the model reasonably well represents the temperature and pressure distribution in the Amatitlán geothermal system.

7. PRODUCTION HISTORY MATCHING

The production history calibration for the Amatitlán system focuses on matching the mass flow rate and flowing enthalpy from November 1998 to May 2019. For the case of Amatitlán, the production history simulations required the following steps:

1. Identify depth of main feedzones production and injection wells and assign them to specific elements in the model.
2. Estimate productivity indices and feedzone pressures.
3. Percentage of the control valve opening of each production well are applied to throttle or even shut each well during the production. history simulation.
4. A fixed injection rate was set up for each injection well.
5. Run production history simulation for 20 years and 7 months (November 1998 to June 2019).
6. Steam flow for each well was calculated using the historic separator pressure data for their corresponding separation station.
7. DELT generator was used to compensate valve opening and effects of calcite scale in well AMF1RD.

The whole production history simulation process was controlled with Py-TOUGH scripts. The scripts not only automated the simulations but also avoid human error when setting up complicated simulations and it can also be easily extended if the model needs further refining. The key calibration parameters were the fracture permeabilities and porosities in the production zones and the well productivity indices. Each change on permeability required re-running and re-calibrating the natural state model. A well-bore simulator developed, for internal use only, by Geothermal Institute at the University of Auckland, New Zealand, was used to determine the feedzone pressures. The wellbore simulator can be coupled with another software (PEST) for automation of the matching process of measured data. In this way, different well-bottom pressures can be calculated for different flowing enthalpies and/or mass flow rate changed. The iterative nature of this process and moderate run times combined to make the model calibration time consuming.

Figure 11 shows the production estimates for selected wells. The matches are good, for example the gradual decline in production rates have been matched for most of the wells, as well as the enthalpies. Old AMF1 shows a decrease on mass flow rate over time, but the enthalpy remains stable. In some extend, the model was developed to match this decrease on mass flow rate due to calcite scaling by adjusting the model parameters. The model is reproducing very well production from the wells AMF5, which shows important features such as the low mass flow rates and high enthalpy (dry steam). This indicates the existences of low permeability structures at depth in this part of the reservoir. As usual in numerical modeling, dry steam or near dry steam enthalpy is difficult to reproduce. In our case, we lowered permeability and porosity of the assigned rock types near the assigned element to the feedzone of the well in order to increase simulated enthalpy. At the end of the simulation the enthalpy drops because some recharge from the surrounding block allows the pressure to increase dropping the enthalpy or due to cooling of the surrounding rocks due to excess boiling. Details of production parameters for each well, including its calibrated productivity index and the bottom-hole pressure obtained from the well-bore simulator, are given in Table 2.

Figures 12 shows simulated and measured flowrates of well AMF1RD. The model reproduces very well the production history of AMF1RD, which is the best producer in the field. Well AMF1RD suffers from calcite scaling as suggested by field data when total flowrate and wellhead pressure decline with time. A mechanical cleaning on 2014 and acid jobs in 2017 and 2019 were performed to recover steam production from this well. The model was constrained to reproduce the calcite scale problem, the model reproduces the mass flow rate and the flowing enthalpy.

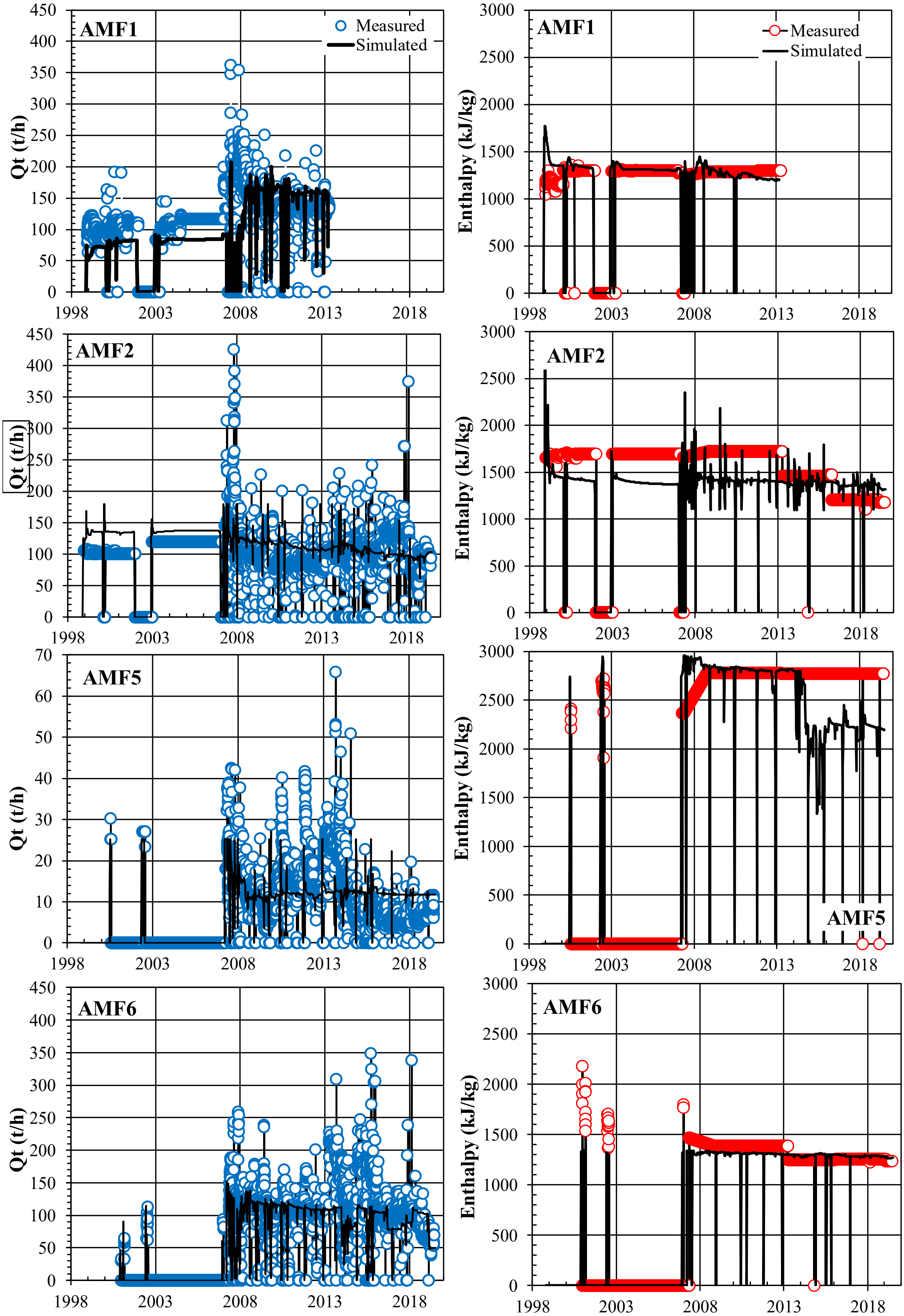

Figure 11: Measured and simulated total flowrates and enthalpies of Amatitlán production wells.

Table 2: Productivity index and bottom-hole pressure for best fit scenario Amatitlán wells.

Well Name	WBP (Pa)	Calibrated PI (m^3)	Well Name	WBP (Pa)	Calibrated PI (m^3)
AMF1 (Feedzone 1)	4.40E+06	2.00E-12	*AMF7 (Feedzone 1)*	3.70E+06	4.30E-13
AMF1 (Feedzone 2)	1.90E+06	6.00E-13	*AMF7 (Feedzone 2)*	1.00E+06	8.00E-11
AMF2	3.60E+06	3.00E-11	*AMF8*	8.75E+05	3.00E-11
AMF5	1.20E+06	3.50E-12	*AMF1RD (Feedzone 1)*	3.50E+06	2.00E-10
AMF6	3.00E+06	1.30E-12	*AMF1RD (Feedzone 2)*	1.40E+06	4.00E-12

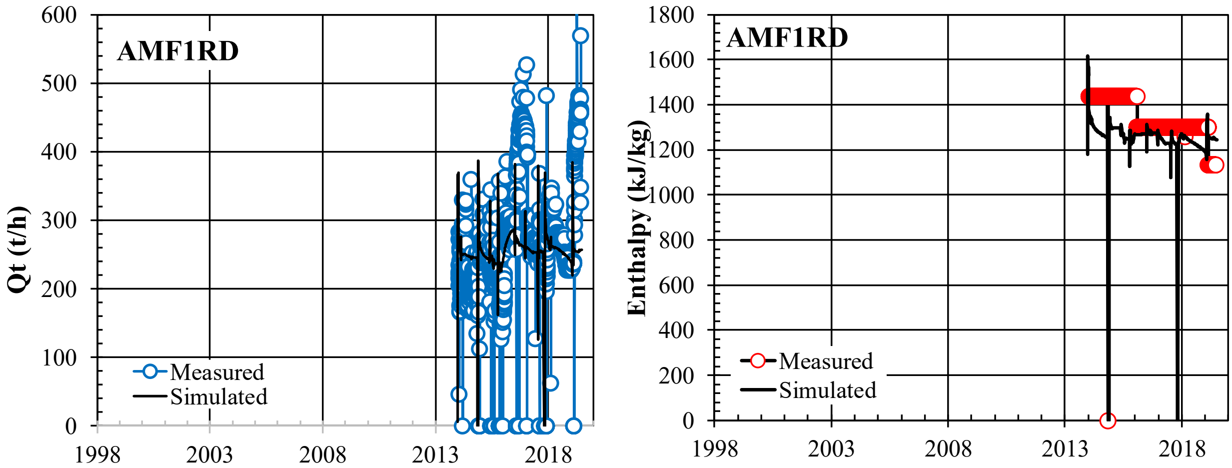

Figure 12: Measured and simulated total flowrate and enthalpy of well AMF1RD.

The DELT AUTOUGH2, Yeh, A., et al (2012) function was used for reproducing production history of AMF1RD. Deliverability generator DELT is a new generator that deals with the operation of geothermal wells, a well under Deliverability Time generator can reproduce the decrease or increase of mass flow rate due to changes on operational conditions or reservoir/wellbore conditions such as scaling within wellbore or in formation. DELT uses a "Feedzone Deliverability Factor" that can be adjust to reproduce decrease of productivity due to scaling problems.

Table 3 shows the logic of DELT generator that assigns to Feed zone 1 a Productivity Index of $2.0e^{-12}m^3$. Start date and End date for this factor to be applied and for a Control Valve opening of 35%. For this time frame of the history matching of AMF1RD, the overall Deliverability will be as follows:

Table 3: DELT generator setup.

Productivity Index (m^3)	Number of Feed zone	Start Date	End Date	CV opening	Deliverability Factor (scaling factor)		Power Contribution
					Start Date	End Date	
$2.0e^{-12}$	1	5/01/2019	5/15/2019	0.35	0.5	0.3	1.0

$$DELT = 2.0\ e^{-12} x\ 0.35\ x\ 0.5\ x\ 1 = 3.5\ e^{-13}\ for\ time\ 5/01/2019$$

$$DELT = 2.0\ e^{-12} x\ 0.35\ x\ 0.3\ x\ 1 = 2.1\ e^{-13}\ for\ time\ 5/15/2019$$

DELT generator will assign a productivity index over the period were the 35% valve opening was operated, from 5/01/2019 to 5/15/2019, and will apply a Deliverability factor of 0.5 to 0.3. In this case a decrease over the productivity index has been achieve from $3.5E^{-13}$ m^3 to $2.1E^{-13}$ m^3. Well production will decrease by this magnitude of the productivity index affected by scaling.

Transient reservoir pressure is an important parameter used for matching during the production history simulation. Downhole pressure was recorded in well AMF7 between 2008 and 2013 and it is now used for calibrating the updated model of Amatitlán. Figures 13 shows pressure in well AMF7 (black solid dots), this decline trend is normal for an exploited geothermal reservoir. It is well known from interference test done in early days at Amatitlán that injection wells AMF3 and AMF4 don't have hydraulic connectivity with the production area, meaning that there is not a pressure support from injection at Amatitlán. Figure 13 also shows that the model reproduces the pressure decline and slope of the decline in well AMF7.

The simulated pressure at the closest model element to the depth where pressure was recorded in well AMF7, is represented by the solid orange line in Figure 13.

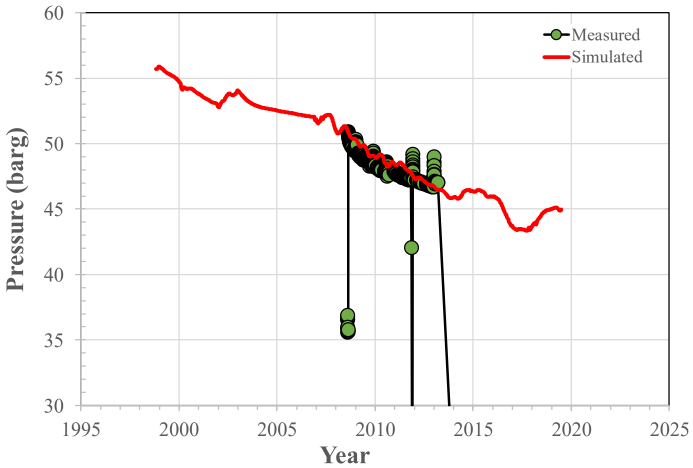

Figure 13: Measured and simulated downhole pressure data of well AMF7.

Simulated gas saturation before started exploitation of the field and in May 2019 are shown in Figures 14(a) and (b). The model suggests that due to the pressure decline in the reservoir the boiling conditions and steam saturation at that depth has increased and the area of two phase conditions has expanded.

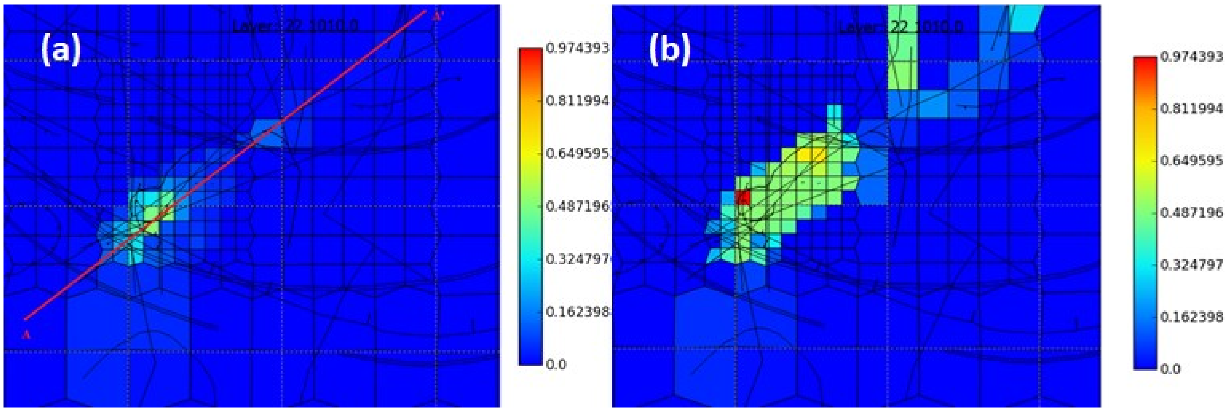

Figure 14: Simulated gas saturation before started exploitation of the field and in May 2019.

8. MODEL FORECASTS

For Amatitlán geothermal system the base fit production history matching model was used to predict the future behavior of the reservoir under the actual conditions. A based line forecast was running until year 2035, results of MW thermal for two different scenarios. The solid green line in Figure 15 represents the first scenario that doesn't consider scale in best production well AMF1RD. The solid red line represents the simulated MW thermal of the scenario where scaling in well AMF1RD is considered in the simulations using the DELT generator; the dashes solid black line represents the liner trend of this second scenario. Both scenarios show a slight decline of about 0.9 MW thermal per year.

The MW thermal difference between both scenarios (solid red line and solid green line in Figure 15) is about 2%, being the MW thermal of the scenario that considers scaling in well AMF1RD always lower than the scenario that doesn't consider scaling. The second scenario is a more realistic approach and helps better to wellfield management on planning.

The new numerical model of Amatitlán geothermal system reproduces in a logic and real sense the field data. In this context, forecast under such a model has a good level of confidence and predictions can be done for resource evaluation under different operative schemes, minimizing risk in decision making.

9. CONCLUSIONS

The existing conceptual model of Amatitlan was revised and updated. This conceptual model was later used for creating a new numerical model that uses state of the art and the latest techniques on pre-and post-processing as well as latest modeling approach using AUTOUTH2 simulator. The new numerical model reproduces measured data during natural state simulations and production history matching. The model is ready for predictions and as an example a base case scenario was run; this base case scenario was divided into two different cases. Scenario one considers continuing production as it is now for the next fifteen years without considering scale in the best production well AMF1RD. The second scenario is the same case as scenario one but it considers scale in wellbore and formation of well AMF1RD. Results of simulated prediction scenarios are that by considering the scale issue during the simulation study, the simulated MW thermal are more realistic that the case that doesn't consider scale. The difference in terms of MW thermal for both scenarios is about 2% lower for the most realistic case. Simulations also show a decline on MW thermal for both cases of about 0.90 MW thermal per year.

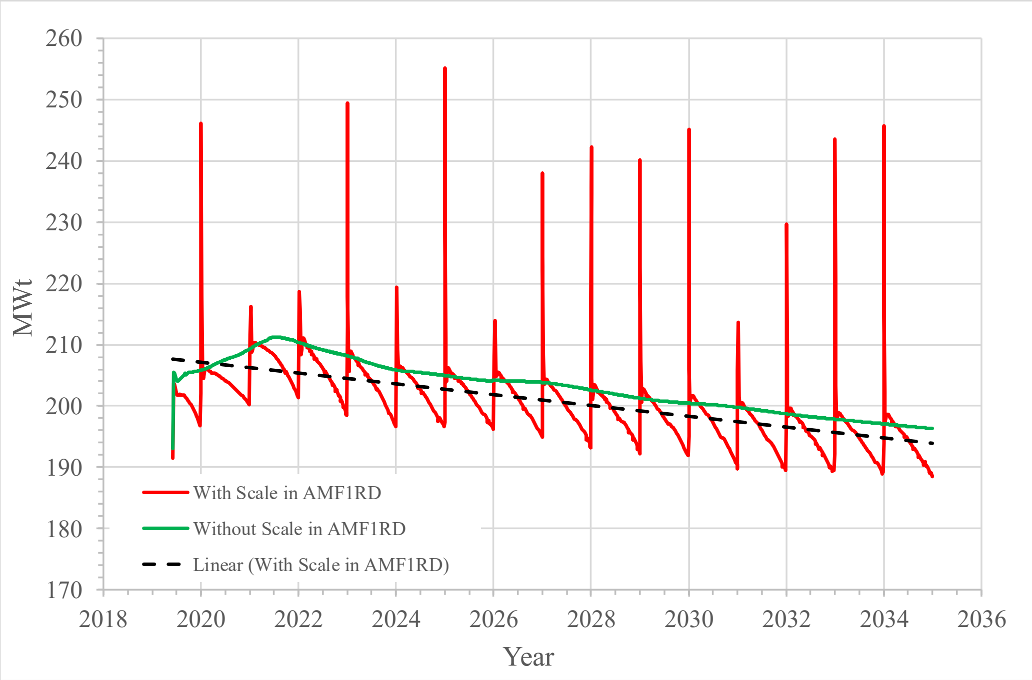

Figure 15: Simulated MW thermal for baseline model ran until 2035 for the without scale and with scale approaches.

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