Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Forty Years of Power Generation at the Ribeira Grande Geothermal Field, Azores

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Keywords: geothermal production, Ribeira Grande, Azores, reservoir management, scaling, reinjection

ABSTRACT

In Azores, geothermal power generation has four decades of experience in the Ribeira Grande field, where the combined production from the Ribeira Grande and Pico Vermelho plants (23 MW_{net}) has been providing up to 44% of the electricity needs of São Miguel Island.

This paper describes the field development, management practices and reservoir response to the production load. The main resource challenges have been related to mineral deposition inside production wells and to the risk of cooling the high-temperature production zones due to reinjection. Proper monitoring, along with geochemistry, tracer testing, and reservoir engineering studies were essential to successfully address these challenges, ensuring the sustainable exploitation of the resource. Likewise, experience and appropriate well intervention techniques allowed to optimize the performance of production and reinjection wells.

With a history of 40 years, geothermal exploitation has not caused any significant impact on the reservoir pressure or temperature. Recent numerical modeling forecasts indicate that the Ribeira Grande reservoir can support an expansion of 5 to 10 MW without the risk of over-exploiting the geothermal resource.

1. INTRODUCTION

The Ribeira Grande geothermal field is in the north flank of Fogo Volcano, the largest one among the three active (dormant) central stratovolcanoes of São Miguel Island. The geothermal system is characterized of a 245ºC two-phase liquid dominated reservoir, hosted in volcanic rocks, that can be intersected by relatively shallow wells (1 to 1,5 km wells). The resource has a fluid enthalpy of 900-1100 kJ/kg and the production wells discharge up to 90-140 t/h at wellhead pressure ranging from 6 to 16 bar-g.

The characteristics of the Ribeira Grande geothermal system are summarized in Figures 1 and 2. In the central part of the volcano, meteoric water seeps down and it is heated by conductive heat originated by a magma chamber or a young intrusion associated with the activity of Fogo Volcano. The upflow of geothermal fluid is inferred to be in the southern part of the field, to the southeast of the current project development. From there, the fluid moves towards northwest following the structure of Fogo volcano and probably with some degree of control by the faults and associated fractured zones of the NW-SE graben of Ribeira Grande (Duffield, 1984; Gandino et al., 1985; Henneberger & Nunes, 1990). The outflow discharges offshore the city of Ribeira Grande, along a narrow zone and within a thin interval (only 200-300 meters thick), and it is apparently controlled by the NW-SE eruptive fissure that originated the Pico das Freiras scoria cone (Franco et al., 2018).

The Ribeira Grande project is divided in three sectors. The high-temperature reservoir has no boundaries limiting these sectors, and this project separation is mainly due to the topographic reasons. The Cachaços-Lombadas (CL) sector is in the southern part of the field, at higher elevation; the Pico Vermelho (PV) sector is in the northern part of the field, at lower elevation; and the Caldeiras sector is in the eastern part of the field, separated of the other two sectors of the field by a deep river creek canyon. Geothermal exploitation is already in place for several years on the PV and CL sectors, whereas the Caldeiras sector has been explored by geophysics (AMT) and deep drillings, which have confirmed the extension of the high-temperature reservoir towards East (Pham et al., 2010; Rangel et al., 2011).

Field development has followed a stepwise strategy. The first exploration works in the Ribeira Grande field were carried out on the late 1970s and they led to the installation of a small pilot plant (3 MW) in Pico Vermelho area in 1980 (Meidav, 1981). This was an important geothermal school for the Azores and supported the next stages of development. Commercial operations began in the 1990s when the 13 MW Ribeira Grande ORC binary power plant was built in two stages on the southern part of the field (5 MW in 1994; +8 MW in 1998). In 2005/2006, the pilot plant was dismantled, and it was replaced by a new 10 MW ORC binary plant in the Pico Vermelho area. Over the past decade, the Ribeira Grande and Pico Vermelho plants have been providing up to 44% of the electricity demand in São Miguel Island.

In this paper, the history of the geothermal development in the Ribeira Grande field, its production results, and the main resource management challenges that were tackled throughout the history of the project are reviewed. In addition, the reservoir response to the production load and the on-going plans for future development are briefly discussed.

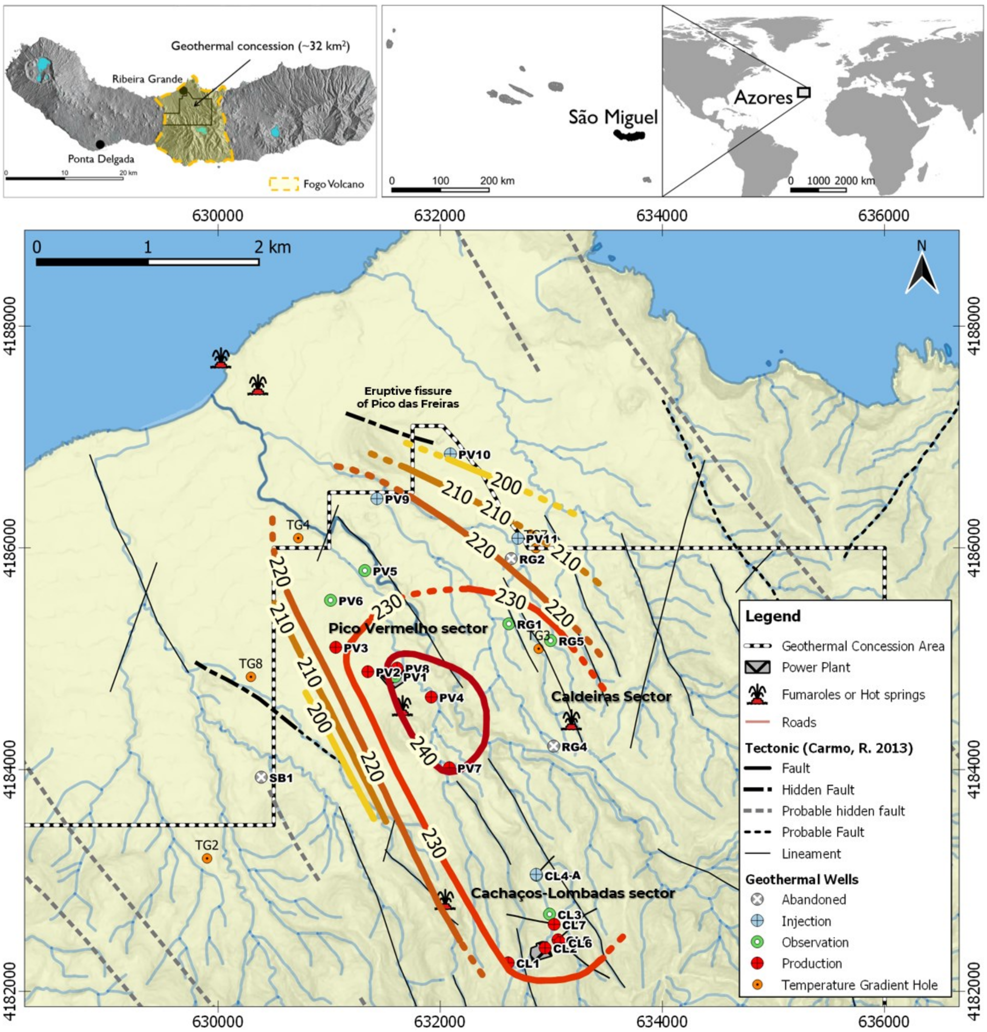

Figure 1: Ribeira Grande geothermal field and temperature distribution at 400 meters below sea level.

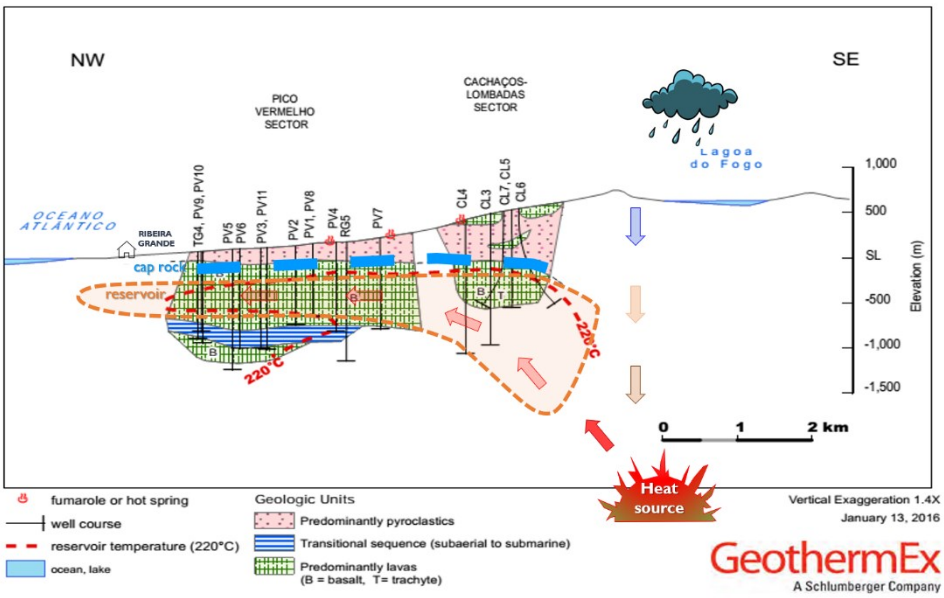

Figure 2: Conceptual model of Ribeira Grande geothermal system (adapted from GeothermEx, 2016).

2. FIELD DEVELOPMENT AND PRODUCTION RESULTS

The first geothermal exploration campaigns were encouraged by the accidental finding of hot water and steam, with a temperature exceeding 200ºC, at about 550 m depth in a cored exploratory well drilled in 1973 close to the city of Ribeira Grande to investigate the formation of volcanic islands in the North Atlantic oceanic crust (Muecke et al., 1974).

The initial geothermal research was promoted by local governmental institutes and the first exploration studies were made in 1976-1977, including geochemical and geophysical surveys and drilling of 8 shallow temperature gradient holes (100-150 m depth). The results allowed to define areas of interest, where five geothermal exploratory wells were drilled from 1979 to 1981 (SB1, PV1, PV2, RG1, and RG2). The first geothermal production milestone corresponded to a small pilot plant (Figure 3) installed in the northern part of the field, in the Pico Vermelho sector. It was a small 3 MW_{net} pilot plant, with a backpressure turbine, built by Mitsubishi and that went online in September-1980. The pilot plant utilized steam from only one producer (PV1) and its average output never exceeded 0.8 MW (Kaplan et al., 2007), not only because of the low productivity of well PV1 but also because of its intermittent service, as there was a frequent need to mechanically clean calcite deposits inside the well (on average, at every 2 to 3 months).

Figure 3: Pico Vermelho pilot power plant (3 MW)

Because of the severe calcite scaling experienced in PV1, the project development to commercial operations was made in the southern part of the field – CL sector, with the intention to move closer to the upflow zone of the system, where higher reservoir temperature was anticipated and therefore it was expected that calcite scaling would be less severe. To promote the geothermal development, a local company was created in 1990 (SOGEO – Sociedade Geotérmica dos Açores, S. A.), fully dedicated to the exploration and exploitation of the geothermal resources of the Azores.

From 1989 to 1994, four wells were drilled, and two of them (CL1 and CL2) supported the Phase A of the Ribeira Grande ORC binary power plant (5 MW), designed by ORMAT, which went online in March-1994 (Ponte, 2002). In the same year, the application of chemical inhibition inside the production wells became a current practice in the field to prevent calcite scaling. This is discussed in more detail in chapter 3. During the initial years of operation, the power plant was producing close to its full capacity, so it was expanded to 13 MW in November-1998 (Phase B), supported by the connection of CL3 as an additional producer. With the start of production of Phase B, reinjection started to be implemented, using CL4 as the only injector. The expansion increased the average power generation from 4-5 to 9-10 MW_{net}, but the geothermal fluid provided by the producers was insufficient to meet the plant power generation capacity. Three new make-up wells were drilled in 2000 (CL5), 2005 (CL6) and 2010 (CL7), and their production kept the average power output of the plant at 9-10 MW_{net} but was not enough to meet the plant capacity. As a result, the Ribeira Grande power plant (Figure 4) has been operating with an average capacity factor of 60-70%.

Figure 4: 13 MW Ribeira Grande power plant

Meanwhile, considering the difficulty to meet the power plant capacity in the southern part of the field, and following the rapid increase in the power demand in São Miguel Island during the '90s, there was a renewed interest for developing also the northern part of the field - PV sector. From 2000 to 2005, six wells (PV3 to PV8) were drilled to support the construction of a new power plant. In 2005, the pilot plant was dismantled, and it was replaced by a new 10 MW ORC binary Pico Vermelho power plant (Figure 5), designed by ORMAT. Since the start of the new plant, production has been guaranteed by the flexible operation of 5 producers and reinjection has been divided by multiple wells (PV5 and PV6 from 2007 to 2014; and shifted into PV9, PV10 and PV11 since 2014). The new producers are very prolific and allowed the plant to be running at full capacity since December-2006 (Franco et al., 2019). In fact, it generates a steady output 11,5 MW_{net}, above the contracted power of 10 MW. This higher performance results from the reserve power capacity of the ORC generation unit and its ability to maximize the excess of geothermal fluid provided by the Pico Vermelho producers, while the generator rated power output was 13 MW_{gross} (Kaplan et al., 2007).

Figure 5: 10 MW Pico Vermelho power plant

In 2014, the company that exploited hydro and wind resources for power generation (EEG), was merged in the SOGEO structure and its designation changed to EDA RENOVÁVEIS, S. A., which continued the work carried out by their parent companies. The history of power generation in São Miguel Island shows that in the '80s and the early '90s, more than 90% of the power generation was based on the consumption of fossil fuels in a thermal diesel power plant. From 1990 to 2007, the growth in the power demand was accompanied by a significant increase in renewables production from 10% to 51%, This energy transition away from fossil fuels was led by geothermal, and the history of renewable power generation in São Miguel Island is directly linked to the steps of geothermal development (Figure 6). Over the past decade, geothermal production has been providing 40 to 44% of the electricity needs of São Miguel Island, originating significant environmental, economic and strategic benefits, and fostering the energy self-sufficiency of the Azores (Rangel et al., 2011; Franco and Ponte, 2019).

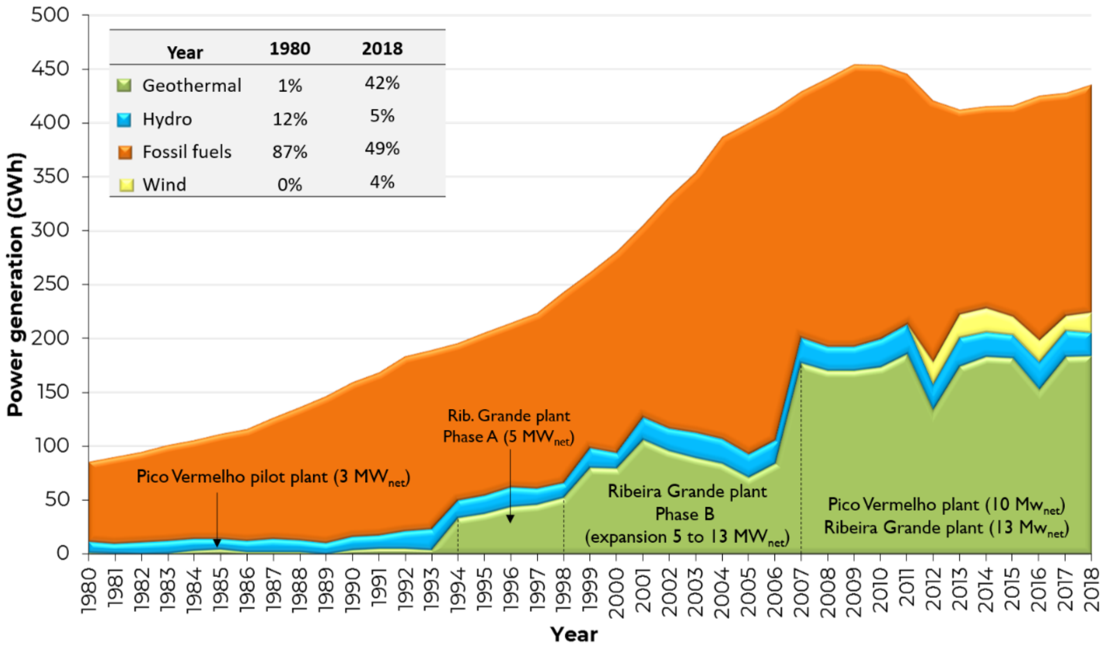

Figure 6: History of power generation in São Miguel Island

3. MAIN RESOURCE CHALLENGES

In the Ribeira Grande field, the main resource management challenges have been related with finding the adequate reinjection location in the northern part of the field to prevent the thermal degradation of the produced fluid temperature and with the risk of mineral deposition, namely of calcite inside the production wells and silica on the plant's heat exchangers and on the reinjection system. The strategies implemented to cope with these resource challenges are described below.

3.1 Reinjection location

The geothermal fluid of Ribeira Grande is a sodium-chloride water, with a salinity of about 6-7 g/l, including a residual concentration of heavy metals. Thus, reinjection is mandatory due to environmental constraints, avoiding thermal and chemical contamination of soil and groundwater, ensuring the disposal of the saline geothermal water downstream the power plants. In addition, as in many other geothermal systems worldwide, reinjection is considered an important tool for the sustainable use of the resource (Axelsson, 2012), contributing to minimize the reservoir pressure decline and thus preventing over-exploitation.

In the northern part of the field (PV sector), from 1980 to 2005 the geothermal water produced by well PV1 was discharged at the surface, in a small nearby river stream, and reinjection only began in December 2006, when the new 10 MW power plant went online. Since then, 400 to 500 t/h of geothermal water, corresponding to more than 94% of the produced fluids, are reinjected back into the deep reservoir. Moreover, reinjection has been divided by multiple wells, guaranteeing operational flexibility. The reinjection wells are at a lower elevation than the power plant and they have good permeability, easily accepting all the geothermal water without the need for pumping.

When the 10 MW Pico Vermelho power plant started production, reinjection was initially divided by wells PV5 and PV6 (located at about 500 m to the north of the production area). Because the resource of the Ribeira Grande field was now being exploited at a higher level than it was in the previous 25 years, a reservoir engineering study was commissioned to investigate the reservoir response to the new production load.

In this scope, a Naphthalene Disulfonate (NSD) tracer test was conducted in 2007-2008, covering the PV and the CL sectors of the field. The results revealed rapid and strong returns of reinjected fluids in wells PV5 and PV6 to the production area of Pico Vermelho, which could cause cooling of the produced fluids (Pham et al., 2010; and Ponte, 2010). Numerical modeling conducted with the support of the consultant GeothermEx confirmed a high risk of thermal breakthrough of the high-temperature reservoir (decline of 1,7ºC/year). To offset it, three new injection wells (PV9, PV10 & PV11) were drilled in the northeast part of the field, farther away from the production area (~1 km) and reinjection was shifted into these wells in 2014. The NSD tracer test was then repeated in 2015, and the reinjection returns were not only slower but also weaker of that observed in the 2007 test, confirming that the risk of thermal breakthrough has been adequately minimized (Rangel et al., 2017). The history of reservoir temperature measured at the main feed zones of the individual wells reflects the success of the relocation of the reinjection, as described in Chapter 4.

In the southern part of the field, initially, the geothermal fluid downstream the Ribeira Grande power plant (Phase A – 5 MWnet) was discharged at surface and reinjection was only firstly implemented with the start of production of the Phase B (expansion to 13 MW). Before Phase B, all four wells were considered production wells; CL1 and CL2 were already feeding the operation of Phase A, CL3 would also be connected as a producer to support Phase B, and CL4, which had the less productivity, was considered a back-up producer. However, with the expansion of the plant, it was planned to start injecting the wastewater and the possibility of using CL4 as an injector was investigated (amongst other possible new drilling sites). In early 1998, injection tests were conducted in CL4 and a tracer test was carried out in the field, by adding a fluorescein dye to the reinjected fluid at well CL4 and collecting fluid samples on the producers CL1, CL2 and CL3 (from the Ribeira Grande plant) and PV1 (from the Pico Vermelho plant). The tests confirmed that CL4 had enough injection capacity to receive all the geothermal fluid without pumping (Granados et al., 2000). On top of that, no returns of fluorescein were detected on the producers, suggesting that it was unlikely that injection into CL4 would cause any significant cooling of the produced geothermal fluid.

Meanwhile, in 2012, and following a leakage repair on the production casing of well CL4 (caused by corrosion), a second injection well (CL4-A) was drilled directionally to the northeast from CL4 wellpad to supplement the injection capacity and increase the operational flexibility in this part of the field. Since 2012, the reinjection of more than 94% of the geothermal fluid downstream the Ribeira Grande plant is being divided by wells CL4 and CL4-A, and they have been accepting all the effluent without pumping. The tracer tests and numerical modeling studies carried out in 2007 and 2015 included also the CL sector. In both studies, it was observed that reinjection returns to the CL production area are very limited, thus with predicted minimal impact on the produced fluid temperature.

3.2 Scaling

The deposition of scales, whether in the geothermal reservoir or the project infrastructures is one of the main challenges faced by the geothermal promoters worldwide (Thorhallsson, 2011). The progressive deposition can cause the obstruction of the wellbore and pipelines and, consequently, originate a decline in the productivity/injectivity of the wells or cause operational problems to the power plant. Amongst the most common deposition minerals are silica, which generally precipitates in the surface infrastructures in the form of amorphous silica, and calcite, whose deposition is usually identified inside the wellbore, just above the zone of first boiling – flash point. Boiling triggers removal of the dissolved gases from the liquid phase (essentially CO_2 and H_2S, which in the geothermal water form weak acids) and, consequently, it causes an increase in pH of the liquid, which can lead to the precipitation of calcite.

3.2.1 Silica scaling

The saline geothermal water tapped in the high-temperature reservoir of Ribeira Grande is prone to form silica deposits by supersaturation upon cooling, with a risk of deposition of amorphous silica on the heat exchangers of the power plant (pre-heaters) and the reinjection system (pipeline and inside the injection wells).

The design of the Ribeira Grande and Pico Vermelho power plants minimized this risk by diluting the silica concentration in the brine, through the mixing of the steam condensate exiting the vaporizer with the hot brine before it enters the pre-heater. Based on fluid chemistry analysis of samples collected on the producers, for the design conditions of the Ribeira Grande and Pico Vermelho power plants it was estimated that silica concentration in the reinjected fluid would be about 380 and 360 mg/kg, respectively. In these conditions, the reinjected fluid would not become supersaturated in silica until is cooled below 95ºC and 87ºC respectively.

Since the start of production from the Ribeira Grande and the Pico Vermelho power plants, the reinjection temperature has been kept above the estimated in the design conditions to minimize the risk amorphous silica deposition (Figure 7). In the meanwhile, monitoring of the chemical composition of the reinjected fluid has shown that silica concentration fluctuates over time, ranging from 400 to 500 mg/l on both power plants (Figure 7). Even though this concentration is slightly above of that considered on the design of both power plants, no amorphous silica deposits were ever found in the power plant heat exchangers nor the reinjection system. Likewise, no significant degradation of the injection capacity has been observed in the injection wells (Figure 8). The reinjection flow rate and pressure are continuously monitored by the power plants control system and the downhole pressure is periodically logged in the injection wells, allowing to determine the fluid level inside the wells and hence follow the evolution of their permeability. The injectivity index of wells CL4-A and PV11 has improved significantly with the sustained injection, whilst well CL4 has a slight decline, and PV9 is the well with the larger decline, though it still is more than capable to accept more than 200 t/h of fluid without the need for pumping.

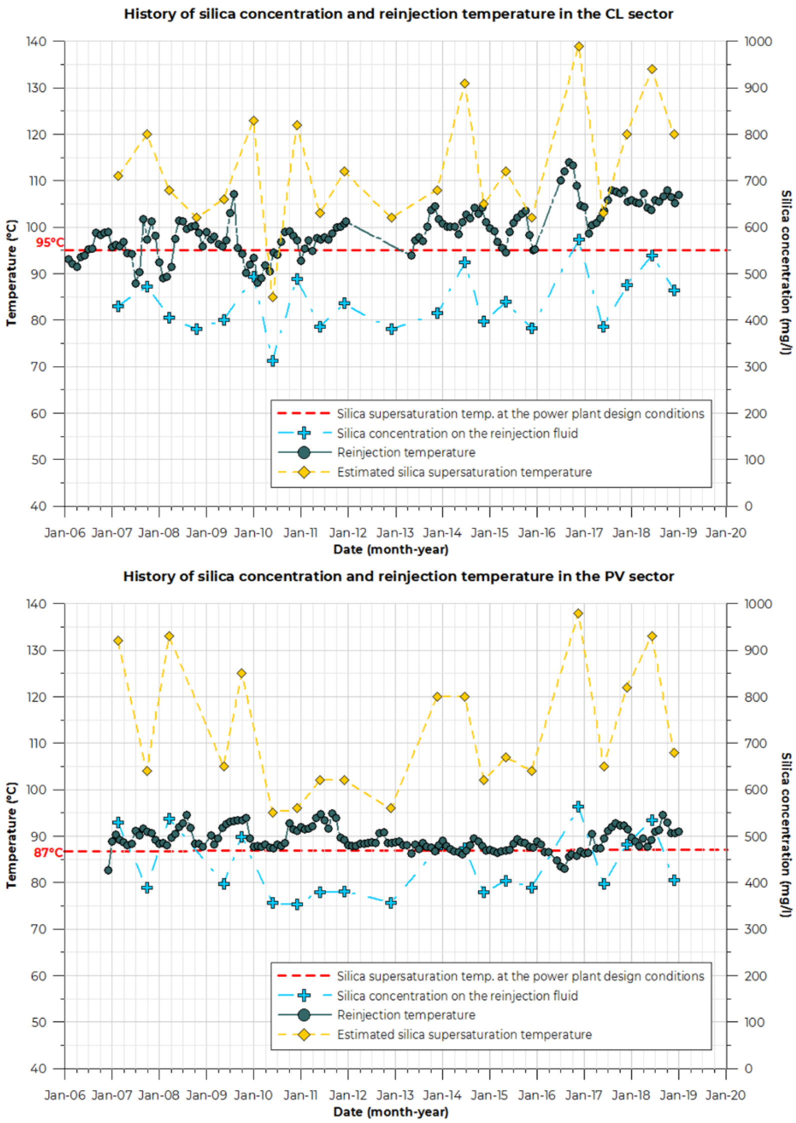

Figure 7: History of silica concentration in the reinjection fluid and reinjection temperature of Ribeira Grande and Pico Vermelho power plants

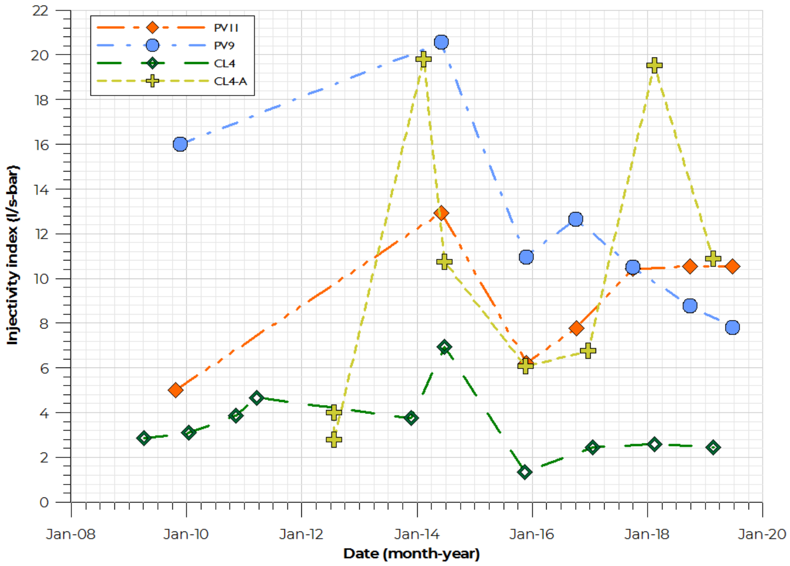

Figure 8: History of the injectivity index on the injection wells of the Ribeira Grande field.

3.2.2 Calcite scaling

Calcite scaling is one of the most common carbonate deposits that occur in geothermal wells and usually is extensively spread in the altered rocks of the geothermal systems, often in the amount of 1% by volume. Normally, the high abundance of deposits of calcite, above 1% by volume, results of a large amount of boiling water rising to upper levels (Arnórsson, 1989) and is quite common in wells drilled in reservoirs with temperature in the range 140-240 °C. Calcite deposition is primarily found where the water starts to boil in the well. Therefore, calcite scales are found over a 200-300 m long section in the well above where flashing occurs but are not found below or above that section (Arnórsson, 1989; Thorhallsson, 2006). The Ribeira Grande geothermal wells fall into this category, tapping geothermal fluid from a reservoir with temperature in the range of 220-245 °C, that is characterized by a vapor-dominated zone overlying a liquid-dominated zone.

The deposition of calcite inside the production wells was particularly challenging to be dealt with in the early stages of the project development. In all the Ribeira Grande wells, while flowing, the zone of first boiling occurs inside the well casing or the slotted liner. Thus, all producers are prone to calcite scaling inside the wellbore, as the geothermal water becomes supersaturated in relation to calcite upon boiling at a flash point temperature of about 220-240ºC (Figure 9)

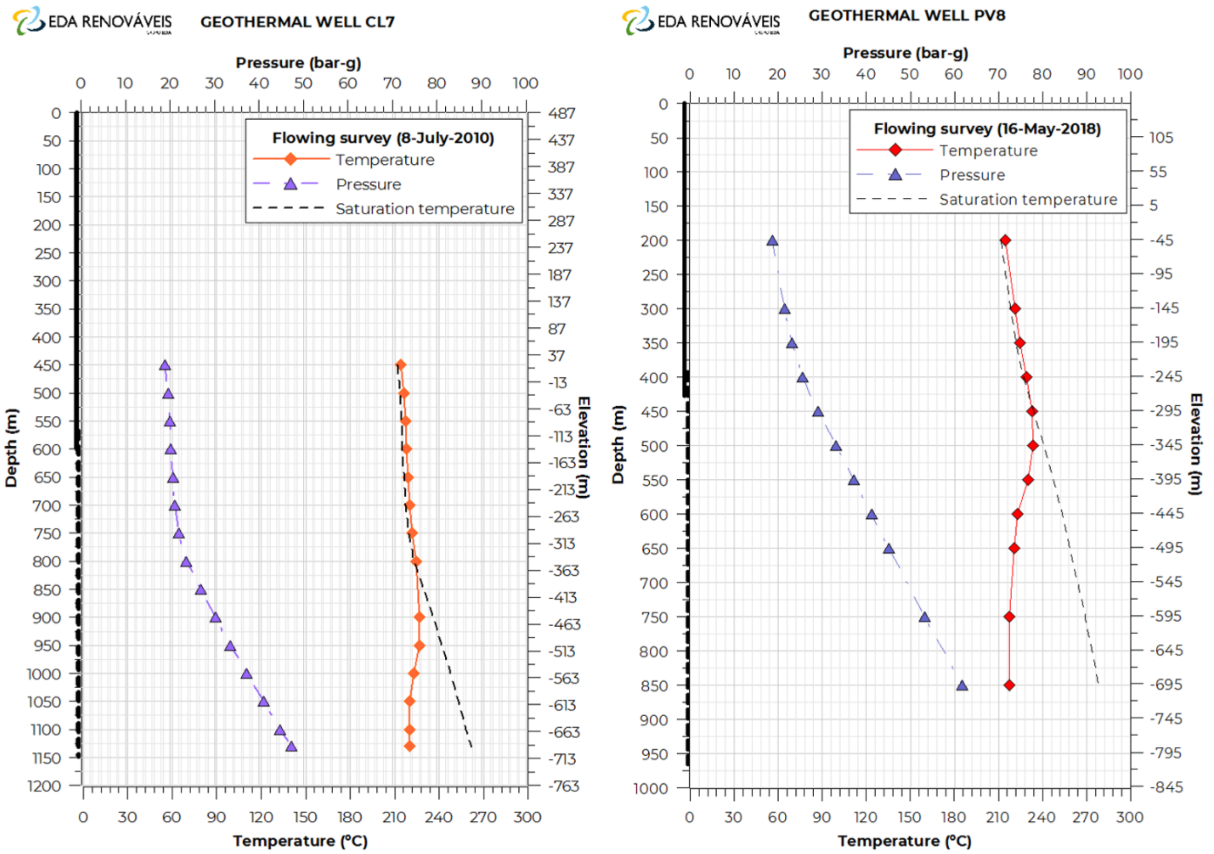

Figure 9: Temperature and pressure profiles of wells CL7 and PV8

In most of the production wells, the deposition has been successfully prevented by downhole injection of a scale inhibitor (Granados et al., 2000; Pereira, 2015). The only exception has been well PV8, where the inhibition system alone has not been able to completely prevent the calcite deposition. To assist with the interpretation of the buildup of calcite scaling in PV8 wellbore, gauge runs (using go-devils) are carried out every month to determine the drift diameter of the production casing and slotted liner. When the obstruction gets severe, mechanical reaming operations are carried out using the Ingersoll Rand RD20 drilling rig owned by EDA RENOVÁVEIS (Pereira, 2015). The clean-outs have been executed on average at every 2-3 years.

The success of the chemical treatment is a result of the cooperation between EDA RENOVÁVEIS and the consultants NALCO and GeothermEx. The inhibitor that has been applied in the field is pHFreedom(R) 5200 M, patented by NALCO (NALCO, 2006). In each production well, repeated field testing allowed to find the optimal dosage and the adequate location for installing the injection chamber (a few tens of meters below the flash-point depth). From the start of production of the Ribeira Grande and Pico Vermelho power plants, the dilution of the inhibitor to the dosage for each well was made manually. However, in 2010, EDA RENOVÁVEIS designed and implemented an almost complete automatized inhibition system, which is has been used until today. The system includes a mixing station (Figure 10), where the chemical inhibitor is mixed with decalcified fresh water to the exact programmed dosage, and then the solution is carried to each wellpad in a tank trailer. At each wellpad, the injection system (Figure 11) includes the electrical metering pump responsible for controlling the flow rate of the chemical inhibitor to be injected in the well. This injection is made continuously when the well is producing, just stopping for periodic inspection of the downhole tools or for running pressure and temperature logs.

Figure 10: Inhibitor mixing station

In each production wellpad, the inhibitor injection system is composed of the following equipment:

- The inhibitor tank (3 m^3), supplying the pre-diluted inhibitor to the well;
- Metering pump for continuous injection of a small dose of chemical inhibitor, with a maximum working pressure up to 59 bar;
- Lubricator set, consisting of a 5 m long 3” steel pipe with a stuffing box mounted on the top and a ram BOP (valve) connected in the bottom. The lubricator allows the installation of the downhole equipment in the well under pressure;
- Nickel-Iron-Chromium INCOLLOY Alloy 825 capillary tubing (¼" OD), conducts the inhibitor from the surface to downhole injection chamber;
- The downhole equipment consists of the inhibitor injection chamber (high-pressure valve) and a sinker bar is installed a few tens of meters below the flash-point depth.

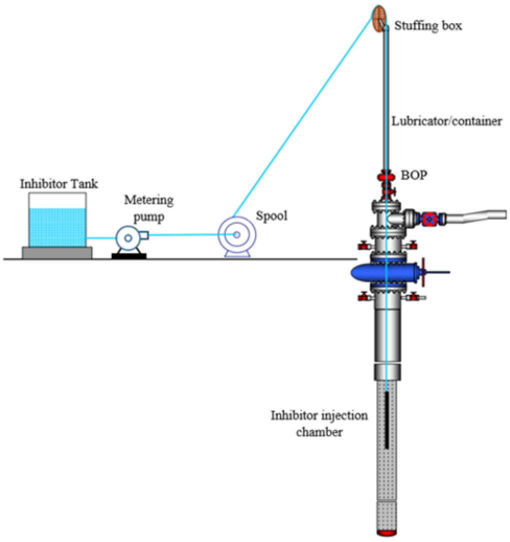

Figure 11: Inhibitor injection system

Regarding the mechanical clean-outs in well PV8, until 2014, it was required to quench the well before and during the reaming operations. This caused temporary cooling of the reservoir formation near the wellbore, and the PV8 had to be put out of service during a period of a few weeks, to allow for the temperature recovery of the reservoir. However, since 2017, EDA RENOVÁVEIS is utilizing a new stripper mechanism (Figure 12) that allows performing the mechanical reaming operations in discharging conditions (Figure 13), without the need to quench the well (Pereira, 2015). With this technique, the temperature in the wellbore and the formation are not affected and the outage period of PV8 is largely reduced. Moreover, the integrity of the casing steel and the properties of the cement bond are also preserved, as there is no thermal cycling due to the changes in temperature.

The list of equipment installed on the wellhead in the calcite cleaning operation is the following:

- PCM (pressure control module) is the main equipment for the cleaning operation and is composed by:
  - A 12" ANSI 900 blind flange, with threaded bore and retaining steel sleeve; and
  - The cooling containment chamber flanged up 7-1/16" and bottom 12" ANSI 900, with 3" side outlet and 1½" outlet pipe.
- 7-1/16" hydraulic pipe ram Blow Out Preventer;
- Tubing stripper, with high temperature rubber, equipped for the entrance of cold water, controlled by two 2" valves (float valve and gate valve);
- One set of 3" valves (gate valve and control valve) at the outlet of the cooling containment chamber to control the pressure inside the module and the discharge of heated water, resulting from the mixture of the cooling water and condensed steam of the well.

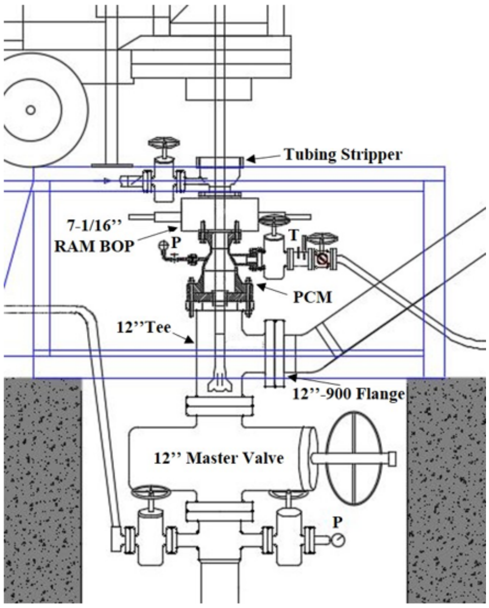

Figure 12: Main equipment assembled in the PV8 wellhead during the calcite cleaning operation (Rangel et al., 2019)

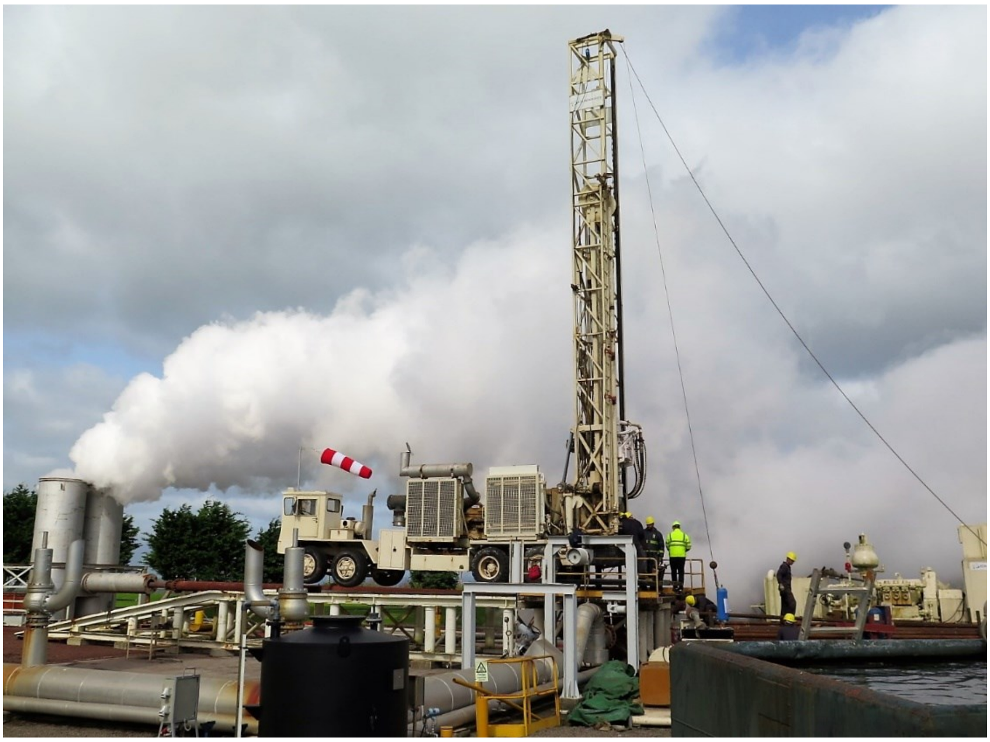

Figure 13: Mechanical reaming while discharging at well PV8 (March-2017)

4. RESERVOIR RESPONSE TO PRODUCTION

The reservoir response to the production load is quite variable and different geothermal systems often respond differently to production, depending on their geological setting and nature. Therefore, comprehensive management is essential for the sustainable use of the resource, with careful monitoring, modeling and reinjection corresponding to the main tools used in modern geothermal resource management (Axelsson et al., 2014). In order to interpret the performance of the reservoir and to be able to forecast its long term evolution, EDA RENOVÁVEIS has been implementing a comprehensive resource monitoring program, including downhole pressure and temperature surveys, well discharges (with the more important parameters being the wellhead pressure, the mass flow rates, the fluid enthalpy), and the chemical composition of the discharged fluids.

Reservoir pressure has been monitored in observation wells, using downhole pressure transients. The larger dataset has been compiled on well CL3, on the southern part of the field (CL sector), where pressure is being logged at 1 km depth since 2008. As shown in Figure 14, pressure has been ranging from 44,25 to 46,00 bar-g, with a minimal decline of approximately 0,1 bar/year, which is considered low to negligible if compared to other geothermal projects worldwide. In addition, there is a good correlation between the reservoir pressure and the mass withdrawal in this part of the field, as pressure recovered rapidly when the production rate was lower (related with periodic closing of individual production wells or with outage periods of the power plant itself). On the other hand, higher production rates did not originate any abrupt decline in reservoir pressure.

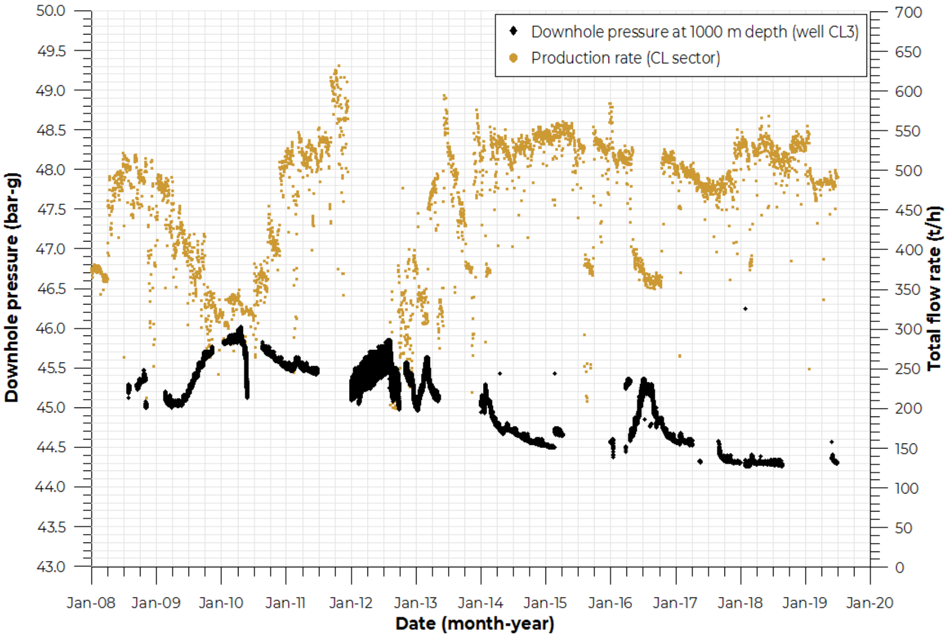

Figure 14: Reservoir pressure measured in well CL3 and production history in the Cachaços-Lombadas sector.

In the northern part of the field (PV sector), reservoir pressure is even more stable. In June-2014, a pressure transient tool was installed in well PV2 and it logged for about 8 months (Figure 15). The results show that although the production rate has seasonal fluctuations (higher in summer and lower during winter), reservoir pressure does not change over time.

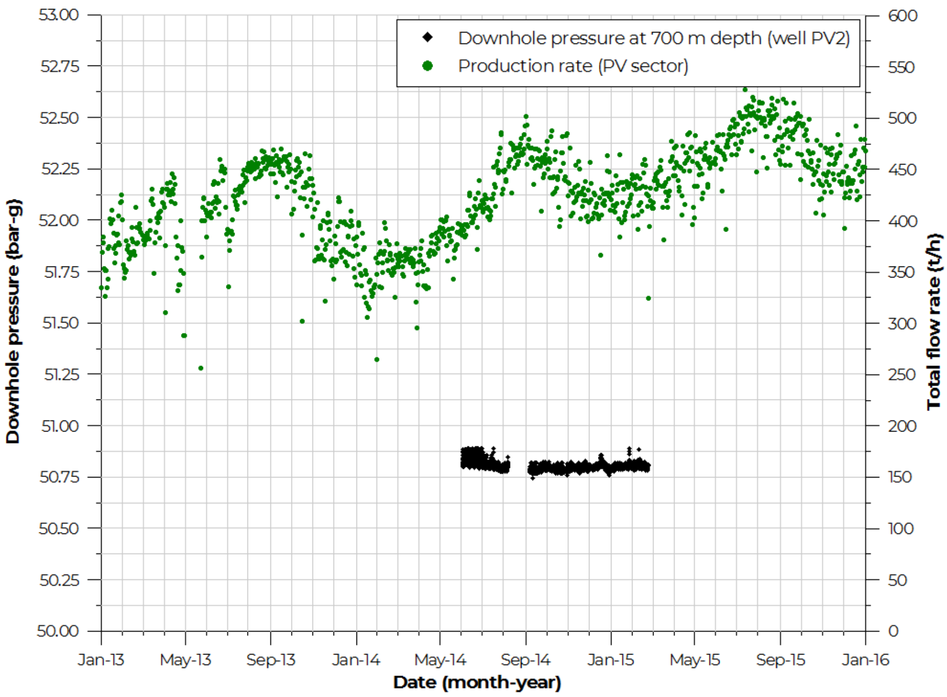

Figure 15: Reservoir pressure measured in well PV2 and production history in the Pico Vermelho sector

As described above in section 3, the 2015 tracer test revealed that returns from the reinjected fluids to the production zones were very weak and slow. Thus, the stable reservoir pressures observed in both CL and PV sectors suggest that most of the discharge is being replaced by the natural recharge. Nonetheless, the reinjection rates practiced in the Ribeira Grande field (more than 94% of the produced fluids) are amongst the highest practiced in the geothermal industry (Kaya et al., 2011; Diaz et al., 2015), and the small returns from the reinjection add to the natural recharge, keeping the pressure support to the production areas of the field and contributing for the sustainable use of the geothermal resource in Ribeira Grande.

On the other hand, the reservoir temperature, measured at the main feed zones of the individual production wells, shows minimal changes over time (Figure 16). In the southern part of the field (CL sector), the temperature is quite stable and homogeneous (except for well CL6 which is the coldest, reflecting its location at the margin of the reservoir), whereas in the northern part of the field (PV sector), the temperature was slightly declining up to 2014 and since then it recovered or remained quite stable. This reflects the success of relocating the reinjection area in the Pico Vermelho sector, placing it farther away from the production zone.

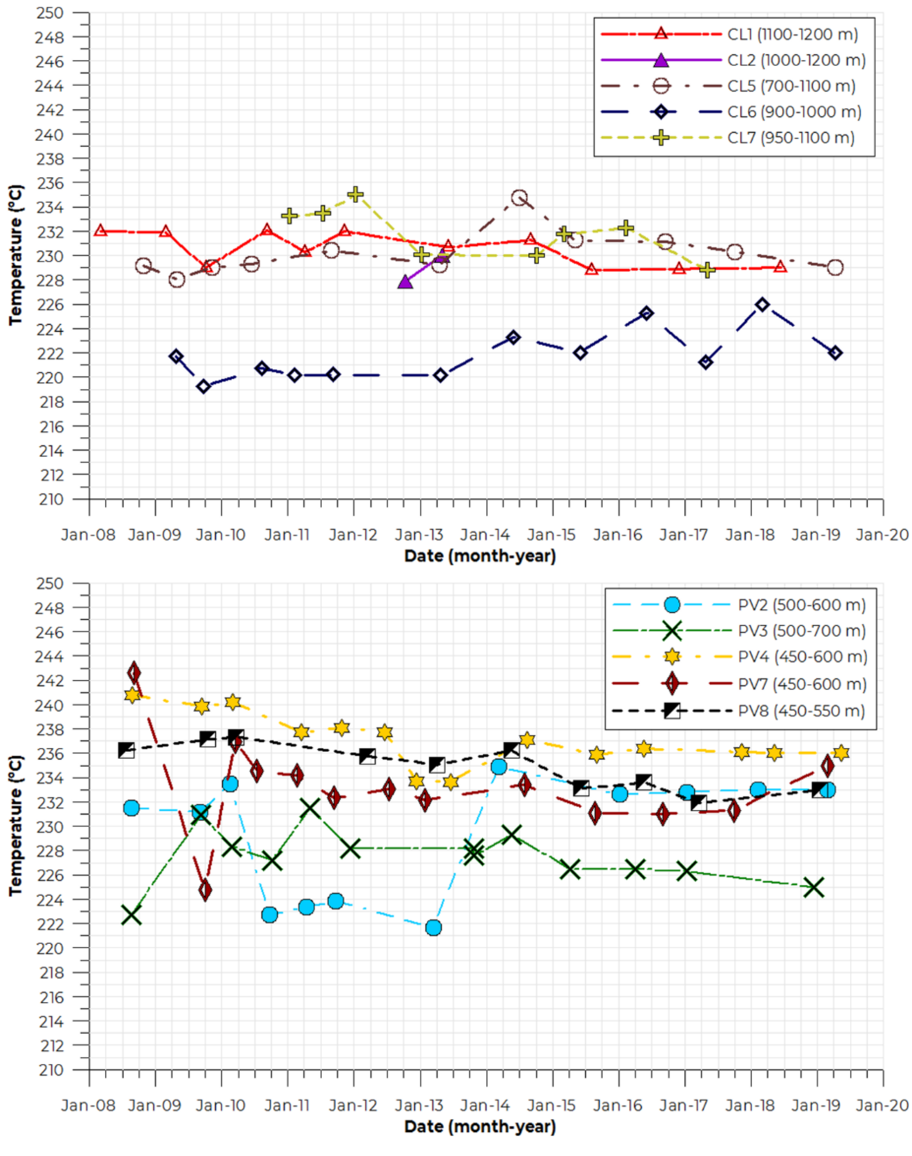

Figure 16: History of reservoir temperature measured at the main feed zones in the production wells.

5. NUMERICAL MODELLING FORECASTS

With the support of the consultant GeothermEx, an update was made to the numerical model of the Ribeira Grande reservoir and forecasts were made to evaluate three different exploitation scenarios for a 30-year period, namely, a non-expansion scenario by keeping the current power generation capacity of the field (23 MW_{net}), and two expansion scenarios of the Pico Vermelho power generation capacity, of +5 MW and of +10 MW, supported by additional drillings.

For all scenarios, the modeling results showed that current reinjection configuration can be maintained without introducing any significant thermal and pressure disturbance to the production areas (Rangel et al., 2017). In the southern part of the field (CL sector), it is expected an enthalpy decline of the produced fluid of about 47 kJ/kg, corresponding to a decline in reservoir temperature of 0,3ºC/year, whilst the pressure decline is expected to be around 0,1 bar/year. In the northern part of the field (PV sector), the predictions indicate slight variations accordingly to the different scenarios, but the expected enthalpy decline is estimated between 21 to 48 kJ/kg, corresponding to a temperature decline in the range of 0,2 to 0,4ºC/year. As for the pressure, it is predicted a decline to be less than 1 bar over the 30-year period.

Based on these encouraging forecasts, there are on-going plans to increase the geothermal power generation capacity in the Ribeira Grande field. In 2020-2021, up to a maximum of six wells are planned to be drilled, three to support the expansion of the Pico Vermelho plant (+5 MW) and another three to meet the Ribeira Grande plant capacity (13 MW).

5. CONCLUSIONS

The utilization of the Ribeira Grande geothermal resource for power generation has 40 years of experience, where the operation of the Ribeira Grande and Pico Vermelho power plants (total of 23 MWnet) has been providing 40 to 44% of the electricity needs of the island throughout the last decade.

The project development followed a stepwise strategy, with each new step being based on the learnings from the previous ones. The main resource management challenges were related to the injection location and the risk of mineral deposition. The strategies implemented on production and fluid reinjection, including comprehensive monitoring of the reservoir response to the production, tracer testing, numerical modeling, chemical inhibition of calcite scaling, and well intervention techniques, have been effective in sustaining the power generation and optimizing the production in both sectors of the field.

The risk of silica deposition has been successfully minimized by keeping the reinjection temperature at or just slightly below the silica supersaturation temperature. No silica deposits have ever been observed in the reinjection system or any significant negative impact had been identified on the injection wells.

Calcite scaling inside the production wells has been successfully prevented in most wells by the application of a chemical inhibitor inside the producers. When this was insufficient (well PV8), mechanical clean-outs were made using the drilling rig owned by EDA RENOVÁVEIS. Since 2017, a new stripper mechanism is available, allowing to perform the mechanical clean-outs under discharging conditions, without the need to quench the well. This technique not only avoids cooling the geothermal reservoir, largely reducing the outage period of PV8, but it also preserves the integrity of the casing steel and the cement bond properties.

Reservoir engineering studies allowed to identify the risk of cooling the production area in the northern part of the field (Pico Vermelho area). Reinjection was shifted further away from the production zone and the produced fluid temperature has recovered or stabilized. Furthermore, numerical modeling studies have indicated that current production is sustainable in the long-term and there is room for an expansion of the Pico Vermelho power plant capacity (+5 MW or +10 MW) without the risk of over-exploiting the resource.

ACKNOWLEDGEMENTS

The authors would like to thank EDA RENOVÁVEIS, S.A., for authorizing this paper and providing valuable data from the geothermal project in São Miguel Island.

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