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Well Field Optimization and Expansion Guided by Tracer Testing and Numerical Reservoir Modeling, Ribeira Grande Geothermal Field, Açores, Portugal

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Keywords

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ABSTRACT

EDA Renováveis, S.A. operates two power plants that exploit the 240ºC liquid-dominated reservoir of the Ribeira Grande geothermal field on the island of São Miguel in the Azores archipelago. The two plants – Ribeira Grande and Pico Vermelho – have a combined capacity of 23 MW and presently generate 44% of the total electric energy consumption of the island and 23% of that of the archipelago.

In 2015 a tracer test using naphthalene sulfonate and disulfonate tracers was conducted to evaluate the hydraulic communication between the injection and production wells of the field. The main goal of the test was to verify the effectiveness of relocating injection in the Pico Vermelho sector, where earlier (2007 – 2008) tracer testing and numerical reservoir modeling had predicted severe cooling as a result of injection breakthrough.

The results of the 2015 tracer test, along with recent information provided by new wells, exploitation data, logging, testing and sampling were used to update the numerical reservoir model and generate field-performance forecasts under the new injection configuration. The results indicate that cooling will be minimal under the current scheme of exploitation, and that the reservoir can sustain an increase of generation from the Pico Vermelho sector and maintain the current output from the Ribeira Grande power plant for 30 years, with only about one make-up well needed.

1. Introduction

One of the most important and challenging tasks in sustainable management of geothermal resources is related to the reinjection of the geothermal fluid after its heat is extracted for conversion into electricity. Although injection is essential to avoid environmental contamination, minimize surface subsidence and manage pressure draw-down caused by mass extraction, the injection of fluid at a relatively low temperature can cause a cold-front breakthrough. This often occurs due to strong hydraulic connectivity along direct flow-paths, such as open fractures, allowing rapid circulation to the production areas of the reservoir, causing it to be cooled in the medium to long term. The premature cooling of production areas is a scenario that has been recorded in several geothermal fields. Therefore, the proper balance with injection between providing the right pressure support to the reservoir and avoiding the cooling of the production wells is one of the most challenging tasks with operational management of geothermal resources.

Tracer testing is an important geothermal reservoir engineering tool that can be used to assess and predict the impact of reinjection on the decline of temperature of production wells, because it provides information on the nature and properties of the flow paths that connect injection and production wells. The value of tracer testing lies in the fact that tracer transport is orders of magnitude faster than cold-front advancement from reinjection wells towards production wells, thus allowing a prediction about the potential for injectate break-through to be made with tracer data (Axelsson, 2013).

This paper describes the results of a comprehensive tracer test conducted during 2015 – 2016 in the Ribeira Grande geothermal field. The test helped to characterize and understand the hydraulic connection between the production and injection wells and helped in calibrating the numerical model of the reservoir, which was used to generate important forecasts of field performance under different operating scenarios.

2. Ribeira Grande Geothermal System

2.1 Geologic Setting

The Azores islands straddle the mid-Atlantic ridge along a NW-SE trend, emerging from the sea in the North Atlantic Ocean from a thick and irregular area of the oceanic crust roughly limited by the 2,000 m bathymetric curve that defines the Azores Plateau. The complex geodynamic setting of the triple junction of the American, Eurasian and Nubian lithospheric plates leads to frequent seismic and volcanic activity in the region (Figure 1).

The Ribeira Grande geothermal field lies on the northern flank of the Fogo volcano (also known as the Água de Pau Massif), the largest of the three active volcanoes in the central part of the island of São Miguel (Figure 2). The volcano has a summit caldera and is composed of a succession of trachytic to basaltic lava flows, trachytic domes, scoria cones, pyroclastic flows, lahars, pumice and ash deposits. The oldest, poorly exposed deposits date from more than 200,000 years ago. The most recent activity of the volcanic complex was a sub-plinian eruption in 1563 that was followed by an effusive basaltic eruption and a hydromagmatic explosive event in 1564 (Wallenstein et al., 2007; Moore, 1990).

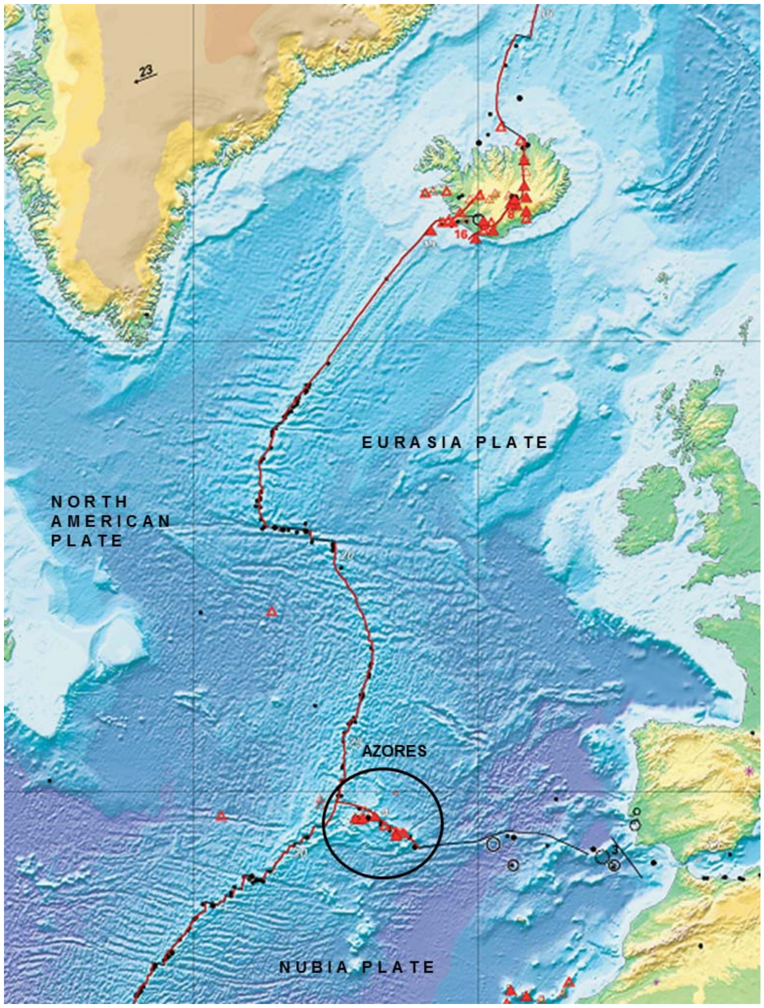

Figure 1: Geotectonic setting of the Azores Archipelago (extracted from Simkin et al., 2006).

The northern flank of the Fogo volcano is down-faulted by a NW-SE trending tectonic graben. It is also possible to identify NE-SW alignments and a circular system of faults, which might be responsible for the emplacement of trachytic domes on the upper part of the volcanic edifice (Wallenstein et al., 2007).

Several geothermal manifestations are present on this active central volcano, mainly on its northern flank. These include fumaroles, steaming ground, diffuse soil degassing areas, and both hot and cold CO_2-rich springs. Their location is associated with the NNW–SSE fault system that defines the Ribeira Grande graben (Viveiros et al., 2009).

The volcanological characteristics of the area are important to the interpretation of the geothermal system, in that: i) the long-term and continuing magmatic activity associated with the Fogo volcano represents the probable source of heat for the system; ii) the lithological and stratigraphic characteristics of the rock units deposited by the volcano have some degree of influence on the shape, extent and characteristics of the system (by influencing the distribution of subsurface permeability); iii) stresses and structures associated with the volcanic activity may have an influence on the distribution of permeability within the system (GeothermEx, 2016).

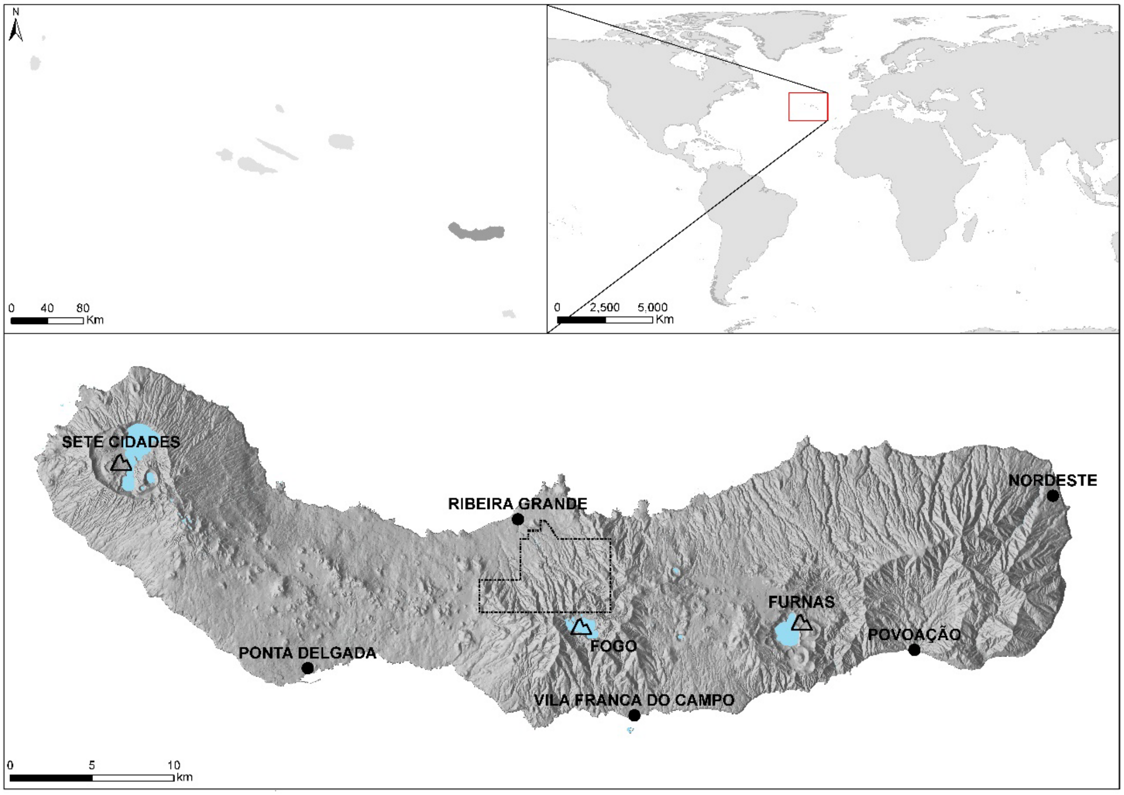

Figure 2: Location of the Azores Archipelago and São Miguel Island, with indication of EDA Renováveis concession area (EDA Renováveis, S.A.).

2.2 Conceptual Model

The Ribeira Grande geothermal field is an extensive, high-temperature geothermal system (with temperature reaching at least 250ºC), hosted by volcanic rocks (mainly a succession of trachytic to basaltic lavas and pyroclastic rocks) on the northern flank of the Fogo volcano. The heat source is probably connected with the body of magma or young intrusive rock from Fogo volcano, and the isotopic signature of produced brine and condensate indicates a meteoric origin for the water in the system (GeothermEx, 2016; Pham et al. 2010; Ponte et al., 2010; Ponte at al., 2009).

Well data from the geothermal field indicate that a sequence of pyroclastic rocks altered to clay forms a relatively impermeable cap at the top of the reservoir. The lower limit of the reservoir (at least in the northwest, lower-elevation Pico Vermelho sector of the field) seems to be formed by impermeable clastic volcanic rocks at or near the transition zone between subaerial and submarine deposits (GeothermEx, 2016; Pham et al. 2010; Ponte et al., 2010; Ponte at al., 2009).

The permeability of the Ribeira Grande geothermal reservoir is associated with fractures in volcanic rocks of the Fogo volcano. The principal flow direction into and within the reservoir at deeper levels is upward and northwestward, following the northwest trend of faulting created by the regional tectonic setting, though there is probably some lateral flow toward the margins of the reservoir as well. At shallower levels (around -400 m elevation), lateral, northwesterly flow appears to predominate over upward flow, forming an extensive, relatively shallow reservoir in the Pico Vermelho sector (GeothermEx, 2016; Pham et al. 2010; Ponte et al., 2010; Ponte at al., 2009).

According to the conceptual hydrological model of the field, geothermal water with a maximum temperature of 250°C enters the reservoir in an upflow zone that is probably located in the southeastern part of the field (east or northeast of the Cachaços-Lombadas sector) (GeothermEx, 2016; Pham et al., 2010; Ponte et al., 2010; Ponte at al., 2009).

The chemical composition of the geothermal water is described by Ponte et al. (2010) as relatively homogeneous throughout the field, being mainly sodium-chloride type with high HCO_3. The reservoir contains predominantly liquid water, but boiling occurs and forms a steam or two-phase zone at the top of the reservoir in some sectors of the field. Progressive boiling of the reservoir water as it flows northwestward reduces the content of non-condensable gases in the Pico Vermelho sector compared with the Cachaços-Lombadas sector, although the difference is generally minor and does not suggest that boiling is extensive (GeothermEx, 2016).

3. Exploitation Scheme

EDA Renováveis, S.A. (owned by EDA – Electricidade dos Açores, S.A., the electric power utility of the region) operates two binary organic Rankine cycle (ORC) power plants: Ribeira Grande and Pico Vermelho. The power plants, which began operation in 1994 and 2006, respectively, have a combined capacity of 23 MW_e and are supplied by deep wells drilled into the Ribeira Grande geothermal reservoir. The exploitation scheme also includes the reinjection of all the geothermal fluid after its heat is used to generate electricity at the power plants. Figure 3 shows the location of the existing wells in the two sectors of the field (designated Cachaços-Lombadas and Pico Vermelho).

Figure 4 provides a NW-SE cross-section through the Pico Vermelho and Cachaços-Lombadas sectors of the field showing the general volcanic stratigraphy, traces of deep production and injection wells, and the 220°C isotherm. As the figure indicates, there is a significant correlation between the distribution of temperature and the positions of major rock units.

To support the development of the geothermal field, the conceptual model of the Ribeira Grande reservoir was created and a numerical model was first developed in 2003. In 2008, the numerical model was re-calibrated using up-to-date temperature, pressure and production data from the geothermal wells, and data from a tracer test conducted in 2007-2008. The updated model was used to generate forecasts of the reservoir performance under various possible injection configurations. This yielded important indications of how power production from the geothermal resource of the Ribeira Grande field could be maximized, while minimizing potential detrimental impacts caused by return of injected water (GeothermEx, 2008).

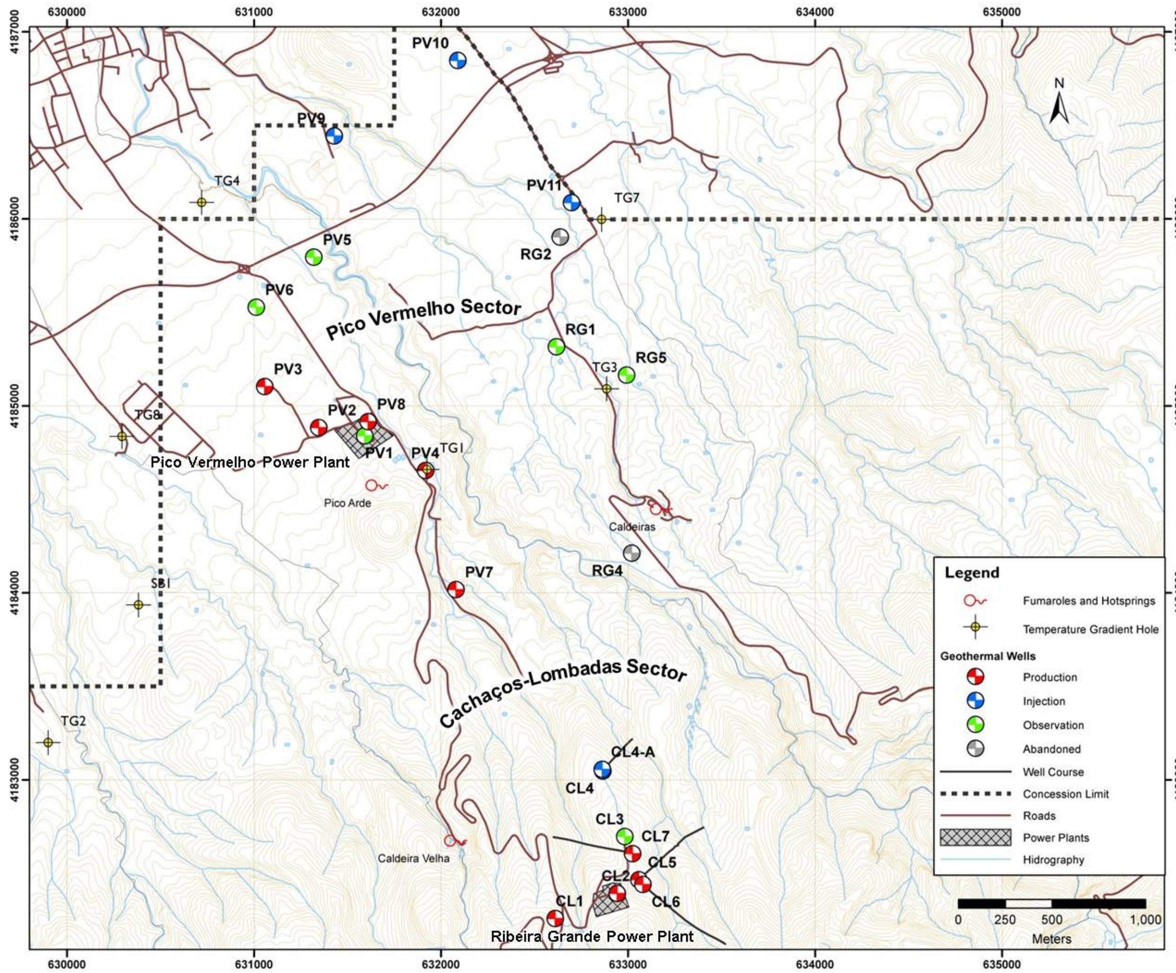

Figure 3: Ribeira Grande geothermal field. Datum WGS 84, Zone 26S (EDA Renováveis, S.A.).

According to those forecasts, continued injection into wells of the Pico Vermelho sector that were in use at that time (injection wells PV5 and PV6) was likely to induce significant thermal breakthrough in the Pico Vermelho production wells, causing a reservoir temperature decline of about 50ºC over the next 30 years of production. Based on those cooling predictions, later confirmed by downhole measurements, EDA Renováveis, S.A. decided to relocate the injection area of the Pico Vermelho sector. In 2009 and 2010, three new injection wells (PV9, PV10 and PV11) were drilled to the northeast of wells PV5 and PV6 and further from the production area.

In 2012, a second injection well (CL4A) was drilled in the Cachaços-Lombadas sector in order to continue operating the Ribeira Grande power plant without depending on a single injection well (CL4), which at that time was more than 19 years old.

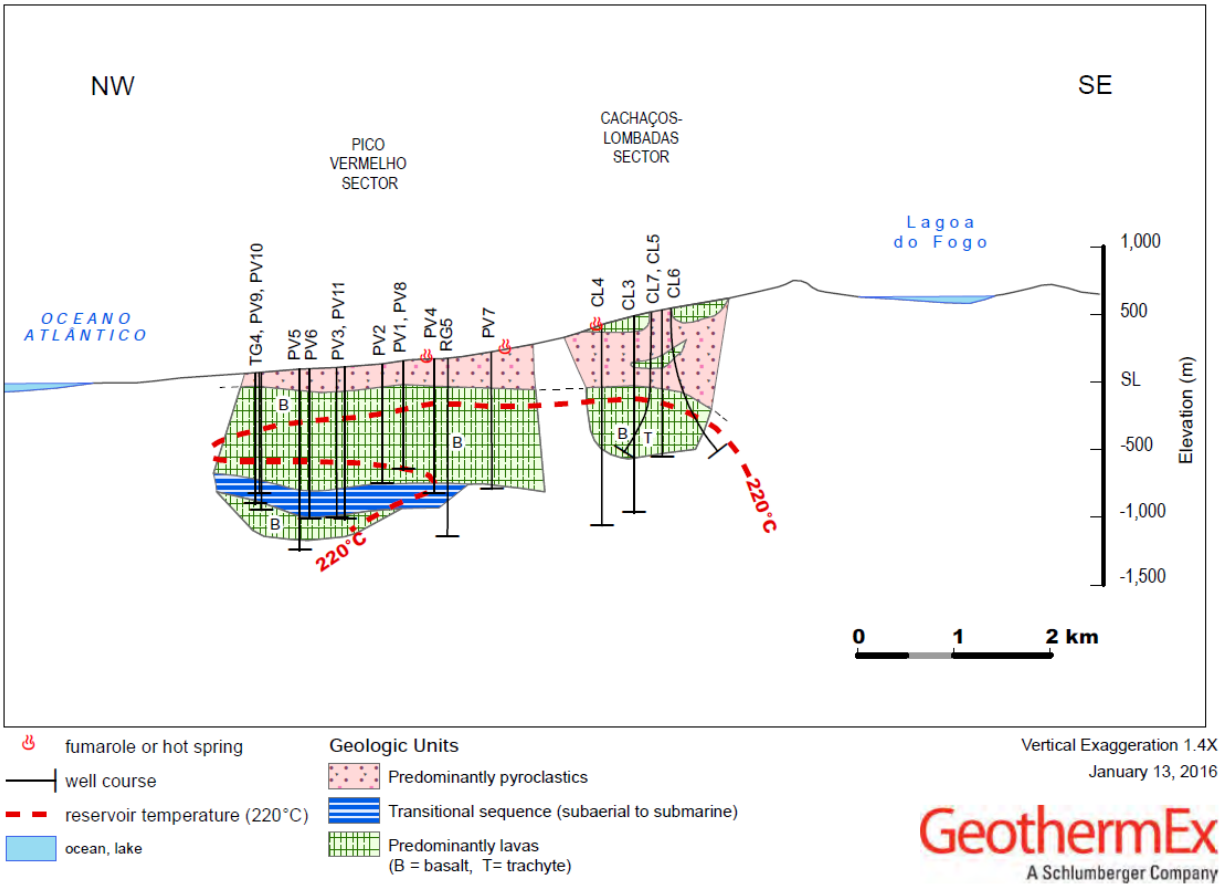

Figure 4: Cross-section through the Ribeira Grande geothermal field (GeothermEx, 2016).

4. 2015-2016 Tracer Test

4.1 Tracer Test Operations

Successful application of naphthalene disulfonate (NDS) tracers during the 2007-2008 tracer test motivated their use again for the 2015-2016 test. The thermal stability of NDS isomers in high-temperature reservoirs, their facilitation of simultaneous multi-well testing, and their compliance with environmental regulations were the main reasons for their selection. Data quality was good in the previous test (as reported in Ponte et al., 2010), so the same NDS tracers were chosen, with the addition of a naphthalene sulfonate acid (for well PV9) and a naphthalene disulfonate acid (for well PV11).

Approximately one week before tracer injection control samples of brine were collected from all production wells to determine tracer background concentration values. All samples were collected into 125 ml HDPE bottles which were tagged and sealed. Dedicated stainless steel cooling coils were used for each sampling port to avoid cross-contamination. Samples of each raw tracer and 10% solution were then gathered in order to measure purity and prepare the standards to be used for laboratory analysis. The solutions were prepared by dissolving the tracer into 1 m^3 tanks, taking care to avoid cross contamination.

On January 14th (day #0), 1000 L of 10% solution of 1,5-NDS, 1,6-NDS, 2-NS, 2,6-NDS and 2,7-NDS were injected into wells PV11, PV10, PV9, CL4A and CL4, respectively, using 1m^3 tanks and flexible flowlines (Table 1).

Table 1: Details of the injection of 1000 L of 10% solution tracer for each well.

Well	Tracer	Elapsed time	Injected Flow	WHP (bar.g)
CL4	2,7-NDS	32 min.	0.52 L/s	0.2
CL4-A	2,6-NDS	9 min.	1.85 L/s	-0.2
PV9	2-NS	19 min.	0.87 L/s	-0.15
PV10	1,6-NDS	6 min.	2.78 L/s	-0.4
PV11	1,5-NDS	23 min.	0.72 L/s	4

After injecting the tracer, production and injection wells were monitored over a period of 609 days. The sampling frequency was high at the beginning of the test, and based on results of analysis was reduced as the test progressed:

Weeks 1 and 2: 2 samples per day

Weeks 3 and 4: 1 sample per day

Weeks 5 to 8: 3 samples per week

Weeks 9 to 18: 2 samples per week

Weeks 19 to 32: 1 sample per week

Weeks 33 to 87: 1 sample every 3 weeks

A monthly selection of samples was gathered in batches and were shipped for analysis by Energy and Geoscience Institute (EGI) at the University of Utah, Salt Lake City, Utah, USA using Ultra High Pressure Performance Liquid Chromatography (UHPLC). This method provides a detection limit not greater than 0.20 parts-per-billion (ppb). Later, once the preliminary results were interpreted, batches were analysed in 3 to 4 month intervals.

4.2 Tracer Test Results

The maximum concentrations of tracers detected in production wells are represented on Figure 5. Plots of tracer returns for each well where tracers were injected during the 2015-2016 test are shown on Figures 6 through 10. Maximum tracer concentrations in production wells for this test (and the corresponding number of test days when the reference concentration was reached) are summarized in Table 2. Tracer concentrations in background samples from production wells sampled during the 2015-2016 test are summarized in Table 3.

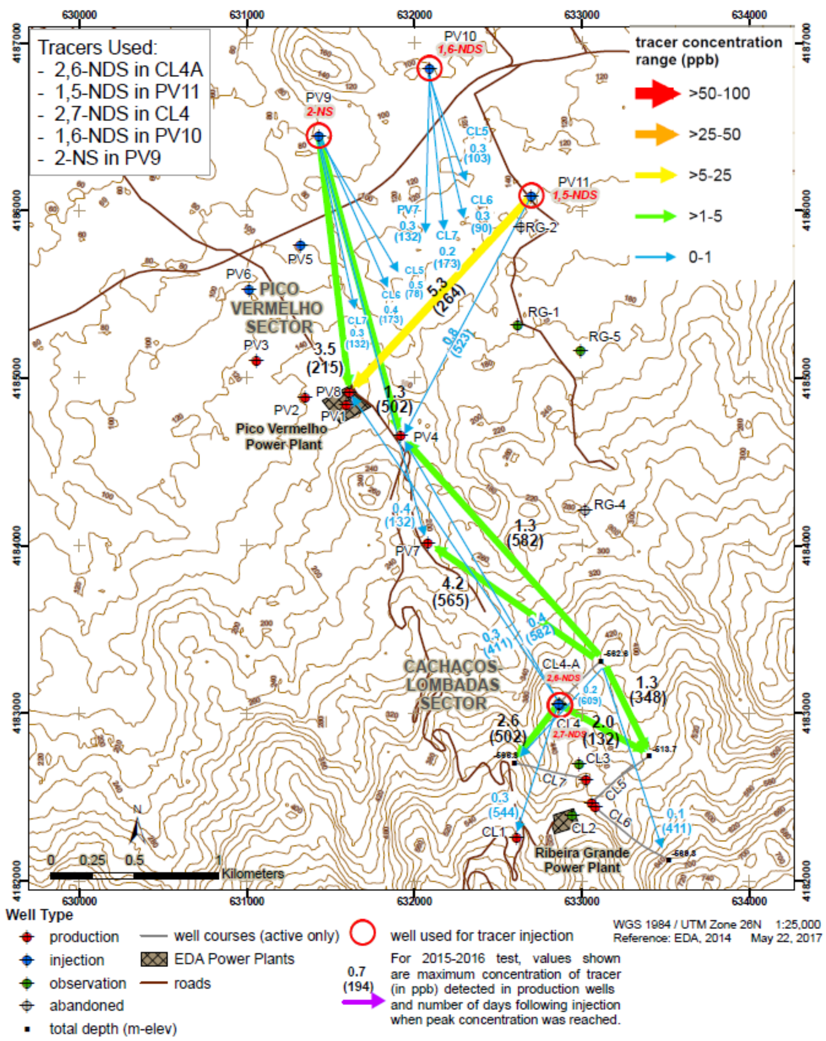

Figure 5: Maximum concentrations detected after 609 days in Pico Vermelho and Ribeira Grande wells during 2015-2016 tracer test (GeothermEx, 2016).

2015-2016 tracer test results	Injection Well	Tracer	Maximum Tracer Concentrations by Well Over 609 Days (ppb): CL1	CL5	CL6	CL7	PV4	PV7	PV8
	CL4	2,7 - NDS	**0.3** (544)	**2.0** (132)	**2.0** (432)	**2.6** (502)	**0.4** (582)	**1.3** (565)	**0.3** (411)
	CL4A	2,6 - NDS	**0**	**1.3** (348)	**0.1** (411)	**0.2** (609)	**1.3** (582)	**4.2** (565)	**1.1** (40)
	PV9	2 - NS	**0**	**0.5** (78)	**0.4** (173)	**0.3** (132)	**1.3** (502)	**0.4** (132)	**3.5** (215)
	PV10	1,6 - NDS	**0**	**0.3** (103)	**0.3** (90)	**0.2** (173)	**1.3** (40)	**0.3** (132)	**1.7** (30)
	PV11	1,5 - NDS	**0**	**0**	**0**	**0**	**0.8** (523)	**0**	**5.3** (264)

Table 2: Maximum tracer concentrations in production wells for the 2015-2016 test. Test duration was 609 days. Tracer return values are shown in bold. Shown in parenthesis is number of test days when maximum concentration was reached.

2015-2016 tracer test results	Tracer	Background Tracer Concentrations Detected by Well (ppb): CL1	CL5	CL6	CL7	PV4	PV7	PV8
	2,7 - NDS	**0.1**	**0.9**	**1.8**	**1.3**	**0.3**	**1.0**	0
	2,6 - NDS	0	0	0	0	**0.6**	0	**1.0**
	2 - NS	0	**0.3**	0	0	0	**0.2**	0
	1,6 - NDS	0	**0.1**	0	0	**1.1**	0	**1.4**
	1,5 - NDS	0	0	0	0	0	0	0

Table 3: Tracer concentrations in background samples from production wells for the 2015-2016 test, collected ~1 week before tracer injection. Tracers in background samples are residual from the 2007-2008 test. Tracer return values are shown in bold.

In the Cachaços-Lombadas sector of the field, only very small concentrations of the tracers injected into CL4 (2,7-NDS) and CL4A (2,6-NDS) were observed at the production wells CL1, CL5, CL6 and CL7. The maximum tracer concentration was 2.6 ppb of tracer 2,7-NDS at well CL7 after 502 days and 2.0 ppb of the same tracer at well CL5 and CL6 after 132 and 432 days, respectively. The concentration of these two tracers detected at well CL1 was not significantly above background level (Figures 6 and 7).

The weak and slow return of tracers 2,6-NDS and 2,7-NDS indicate that injection at wells CL4 and CL4A should not be expected to cause any negative impact on the thermal characteristics of Cachaços-Lombadas production wells. The same conclusions were reached from the results of the 2007 tracer test, when injection from the Ribeira Grande power plant took place only at well CL4.

In well PV4, located in the Pico Vermelho sector of the field, the tracer 2-NS (from PV9) was first detected at a very low concentration (0.4 ppb) after 131 days and showed a peak of 1.3 ppb after 502 days. For the tracer 2,6-NDS (from CL4A), a peak of 1.3 ppb was detected after 582 days (Figures 7 and 8). No significant tracer returns from other injection wells were detected in production well PV4.

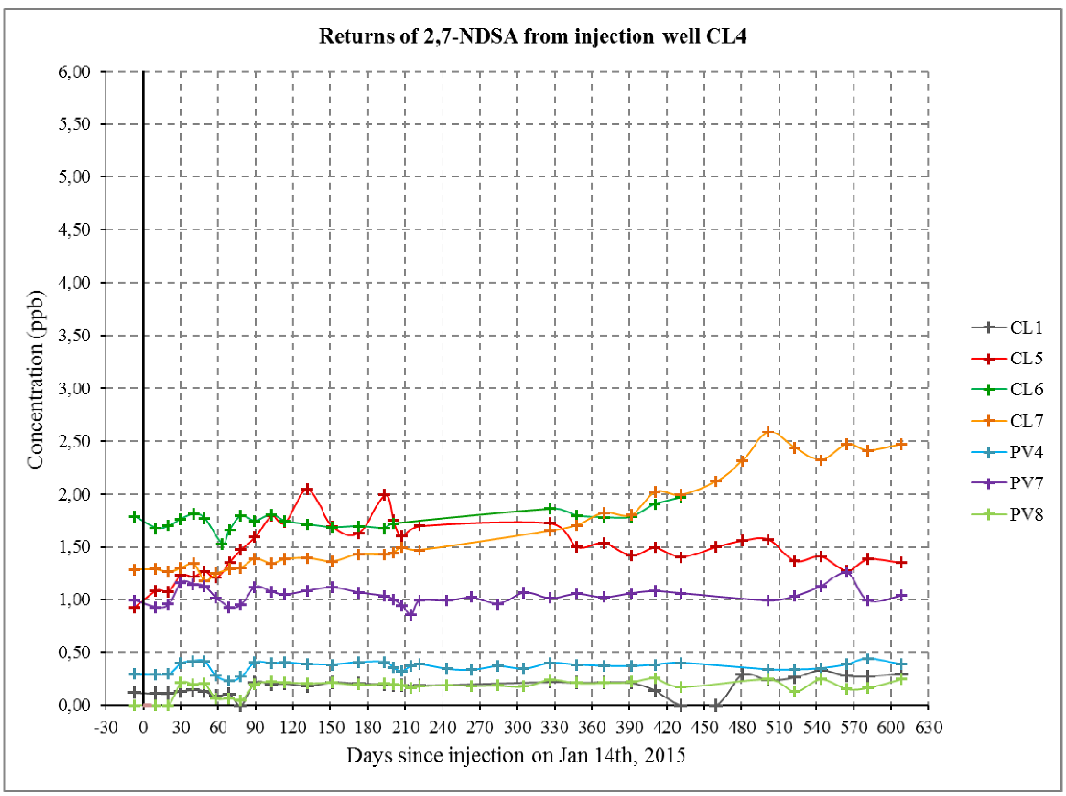

Figure 6: Tracer returns from well CL4.

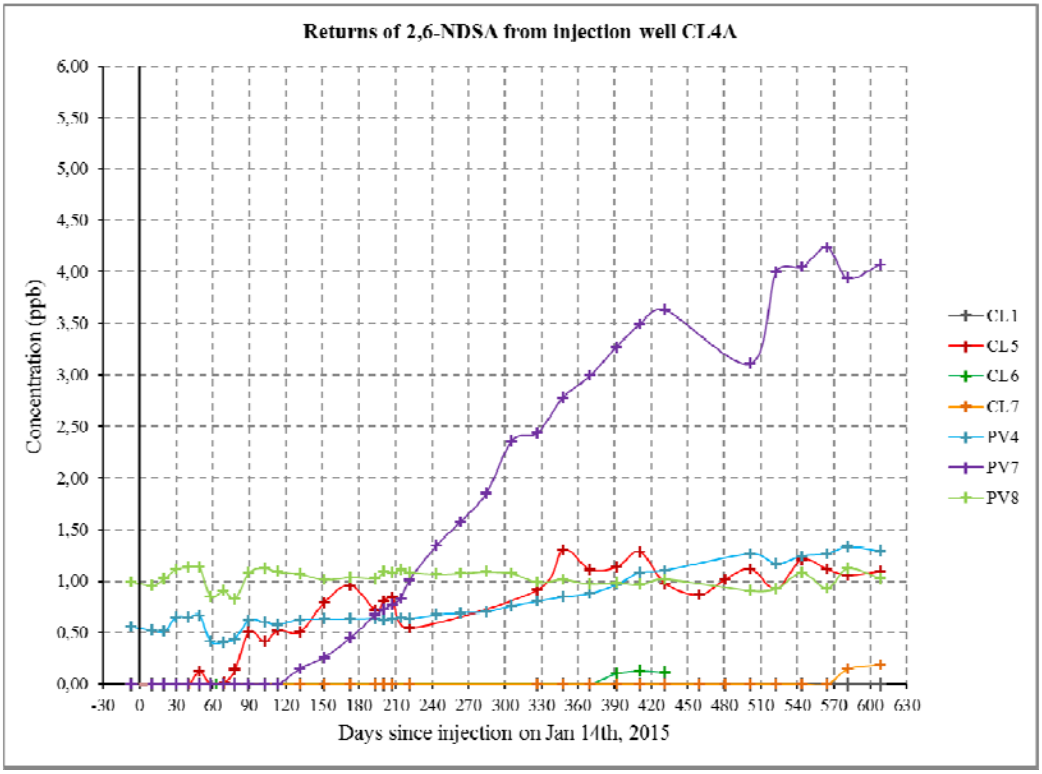

Figure 7: Tracer returns from well CL4A.

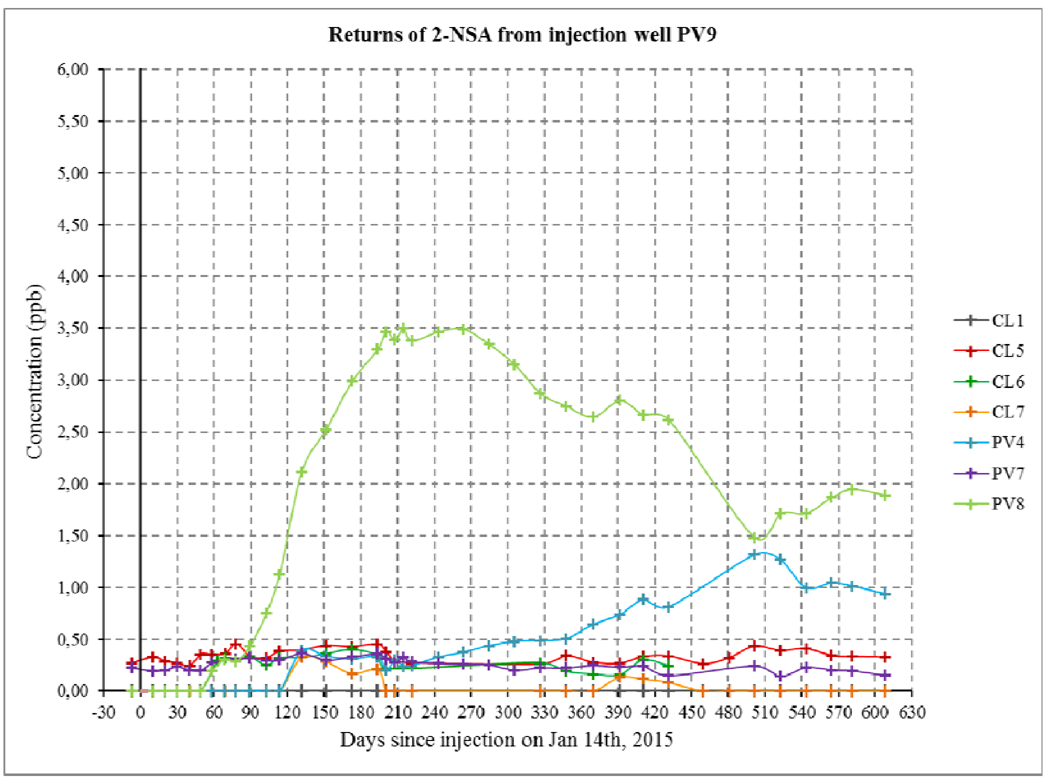

Figure 8: Tracer returns from well PV9.

At well PV7, the most significant return was from tracer 2,6-NDS (injected at CL4A) (Figure 7), which was first detected after 131 days and had a maximum concentration of 4.2 ppb after 565 days. No significant tracer returns from the Pico Vermelho injection wells were detected at PV7.

The results observed at PV4 and PV7 confirm there is a notable hydrologic connection between the Cachaços-Lombadas and Pico Vermelho sectors of the field. This was not observed in the 2007-2008 tracer test, during which none of the tracers injected into PV5 and PV6 appeared in the Cachaços-Lombadas wells nor did tracer injected into well CL4 appear in Pico Vermelho wells (Ponte at al., 2010). Likely explanations are that the 2007-2008 test was run for only 229 days (compared to 609 days for the 2015-2016 test), and that PV7 was not included in the sampling program.

In well PV8, a maximum concentration of 5.3 ppb of 1,5-NDS from PV11 was detected after 264 days (Figure 10) and 3.5 ppb of 2-NS from PV9 was detected after 215 days (Figure 8). No significant returns were observed from tracers injected at PV10 or from the Cachaços-Lombadas injection wells (CL4 and CL4A), as shown on Figure 9.

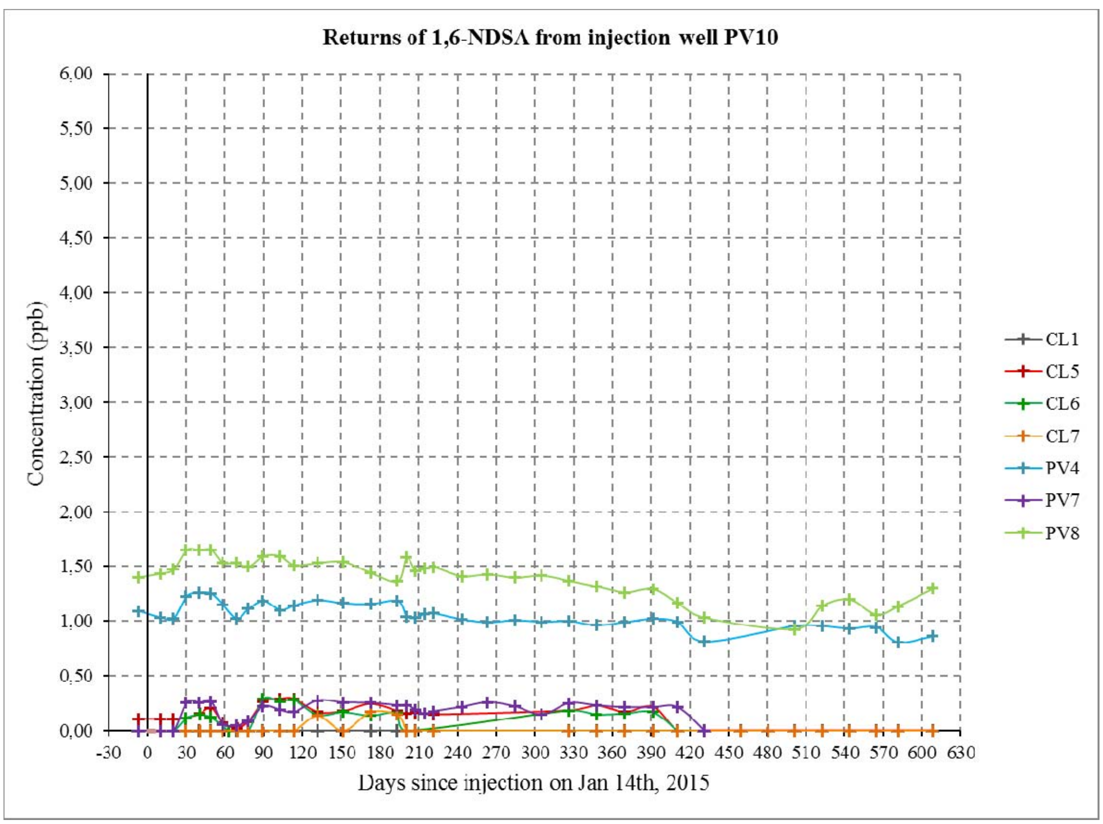

Figure 9: Tracer returns from well PV10.

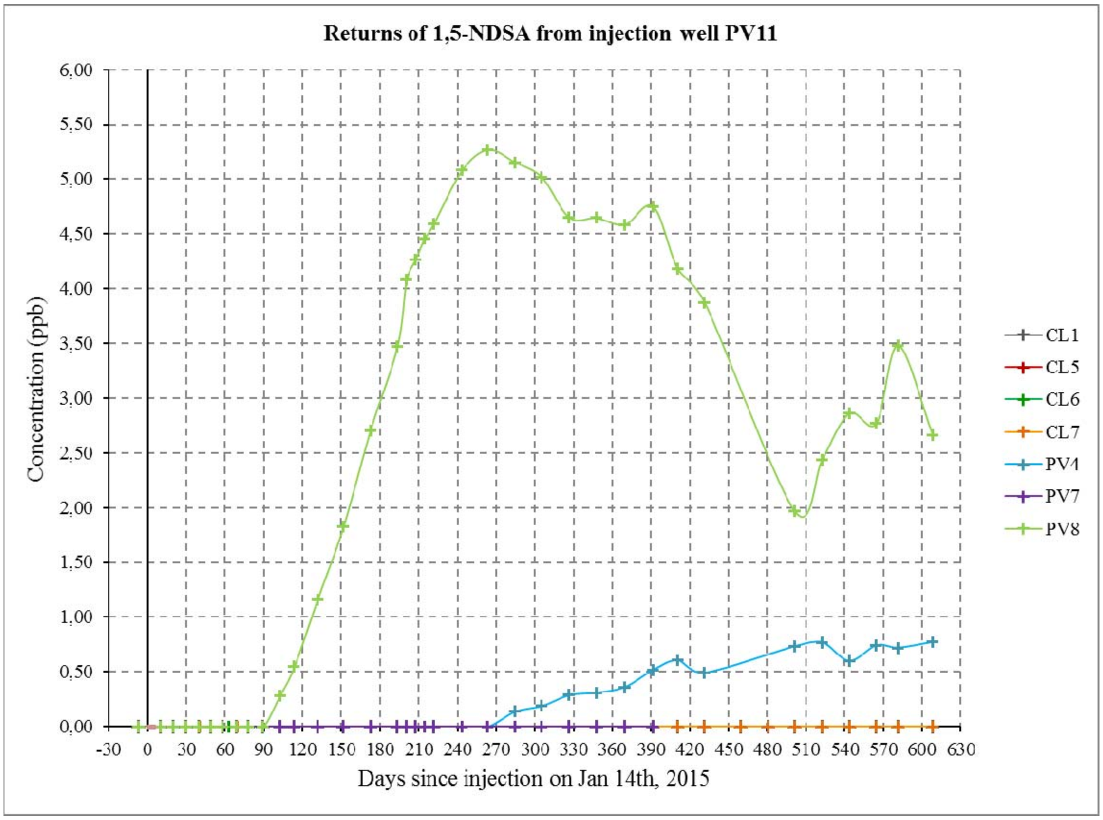

Figure 10: Tracer returns from well PV11.

In the Pico Vermelho sector of the field, tracer return results from the 2015-2016 test are weak compared with the rapid and relatively large-magnitude tracer returns observed during the 2007-2008 test (Ponte et al., 2010). These results can be attributed to the relocation of injection from wells PV5 and PV6 to wells PV9, PV10 and PV11, located approximately 1.5 km farther to the northeast.

4.3 Tracer Background Concentrations

1,6-NDS, 2,6-NDS, and 2,7-NDS were used as tracers during the 2007-2008 tracer test, which were injected into wells PV6, PV5, and CL4, respectively (as further described in Ponte et al., 2010). Each of these tracers were detected in background samples collected approximately one week before new tracers were injected for the 2015-2016 test. Background tracer concentrations in each production well sampled during the 2015-2016 test are summarized in Table 2. Regarding these background tracer data:

- 2,7-NDS was injected into well CL4 in the Cachaços-Lombadas sector during the 2007-2008 test and was detected in nearly all background samples from wells in both sectors of the field at the beginning of the 2015-2016 test, albeit at low concentrations overall. 2,7-NDS is perhaps the most thermally stable NDS (Rose et al., 2001), and it therefore appears likely that detection of this tracer in Pico Vermelho wells is related to tracer transport and diffusion within the reservoir to this sector of the field since its injection in CL4 in October 2007. As first noted above, this concept of south to north outflow may be most supported from the 2015-2016 test by the appearance of 2,6-NDS in well PV7 after 132 days (reaching a maximum concentration 4.2 ppb after 565 days), as this tracer was not detected at all in background samples.

- 2-NS detected in background samples from wells CL5 and PV7 is possibly a decomposition product of other tracers used in the 2007-2008 tracer test, since 2-NS was not used during this test. The presence of this tracer in well CL5 may be a degradation product of 2,7-NDS since its injection in well CL4 in October 2007.
- Overall, concentrations of tracers analyzed in background samples are considered to be low (not exceeding 2 ppb). In some cases, background sample concentrations comprise half to nearly all of maximum tracer detected during the 2015-2016 test (e.g., 2,7-NDS in CL6 and 1,6-NDS in PV4 and PV8). To account for this, background sample concentrations that are arbitrarily 75% or greater of the maximum tracer return are not depicted on Figure 5.
- We note measurement of low-level tracer returns of 1,6-NDS in wells CL5, CL6 and CL7. Background concentrations of 1,6-NDS in these wells are less than 38% of maximum to non-detect and are therefore notable. However, the travel of 1,6-NDS from PV10 to production wells in the Cachaços-Lombadas sector in just 30 to 132 days (the timing for first detection in CL6 and CL7) is considered suspect, in addition to the fact that available data suggest that PV10 intersected an area of the field with relatively low permeability (injectivity index between 0.75 l/s-bar to 1.5 l/s-bar). The presence of 1,6-NDS in the CL5 background sample may indicate the travel of this tracer from PV6 following injection during the 2007-2008 test, or possibly, analytical error. In either case, the result of 0.3 ppb in these wells during the tracer test is sufficiently low enough to not overtly affect the simulation calibration.

5. Cooling Predictions/Field Performance Forecasts

After model predictions based in part on the 2007-2008 tracer test showed a risk of cooling in the Pico Vermelho sector, three wells were drilled in 2009 with the objective of providing injection sites more distant from the Pico Vermelho production area. The new wells (PV9, PV10, and PV11) went into operation in 2014, and the numerical model of the Ribeira Grande reservoir was updated and recalibrated in 2015-2016, taking into account the results of recent field operation and monitoring as well as the results of the new tracer test.

Qualitative evaluation of the new tracer-testing results showed that the potential for cooling under the new exploitation scheme is substantially lower, and forecasts made with the updated numerical model confirmed this result. The potential cooling issue identified by the 2007-2008 tracer test therefore appears to have been adequately addressed by relocating the injection. Some more detailed comments on predicted field and reservoir performance follow.

In the Cachaços-Lombadas sector of the field, the speed and magnitude of the return of water from the injection wells to the production wells has not changed substantially from one tracer testing period to the other. In general, the tracer returns appear to be slightly slower and weaker in the 2015-2016 test than in the 2007-2008 test, indicating that the allocation of some of the injection to well CL4-A (drilled in 2012) has reduced slightly the rate of injection return. Continued injection into CL4 and CL4-A should not have a significant negative impact on the enthalpy of the production wells.

With minimal change in the produced fluid enthalpy over the duration of the production history to date, and with injection returns now predicted to have a minimal impact on temperature even in the Pico Vermelho sector of the field, the main driver of any production decline is expected to be pressure decline in the reservoir. Downhole pressure monitoring of wells CL3 in the Cachaços-Lombadas sector shows that the overall pressure change during 2008-2015 was moderate (less than 1 bar). Pressure decline in the Pico Vermelho sector is also minimal to absent, as suggested by downhole pressure measurements at monitoring well PV2. Since this well was shut in in June 2014, its downhole pressure has been stable at about 50.8 bar. The lack of reservoir pressure change at PV2 indicates that pressure support is adequate even after injection has been relocated to a more distant area.

Minimal reservoir pressure decline can also be inferred from the wellhead pressure trends measured at the production wells (because measured enthalpy has been relatively stable for the last few years, reservoir pressure decline can be inferred from observed wellhead pressures if the production rate remains constant). In the Cachaços-Lombadas sector, wells CL1, CL6, and CL7 have shown relatively constant enthalpy and production rates; hence their wellhead pressure can be used to ascertain reservoir pressure. Very little change in wellhead pressure has been detected at these wells in the past few years, suggesting that reservoir pressure has remained quite stable. Wells with recently stable production rates in the Pico Vermelho sector are PV4 and PV7; their wellhead pressures have also been stable during the last three years, again suggesting that little or no pressure decline is occurring in the reservoir.

The three-dimensional numerical model of the Ribeira Grande field was successfully calibrated against the 2015-2016 tracer data (example plots of these calibration curves are shown on Figures 11, 12, and 13) and the exploitation data described above. The model predicts that, under the existing injection configuration (CL4 and CL4-A in the Cachaços-Lombadas sector and PV9, PV10 and PV11 in the Pico Vermelho sector), there will be no major thermal degradation in the production wells supplying either power plant, while pressure support will still be enough to sustain adequate production levels. A total 30-year decline of about 47 kJ/kg in the total production for the Ribeira Grande plant is predicted by the model. With most of the energy in the liquid fraction (which is predicted to remain constant), the total decline in power generation due to enthalpy change is roughly 3-4% for the 30-year period. The rate of reservoir pressure decline predicted for wells in this sector is also quite low (about 3 bar for the 30-year forecasted duration), and should not cause any significant decline in the production rate.

Under current production conditions for the Pico Vermelho plant, enthalpy is predicted to decline about 21 kJ/kg over the next 30 years, corresponding to a total temperature decline in the produced reservoir of about 5°C, or less than 0.2°C per year. The model also predicts a very small change in reservoir pressure in the Pico Vermelho area (just 1 bar total drop over the 30-year forecast period), which is not anticipated to cause any major decline in the field production capacity. Therefore, the project team believes that power generation in the Pico Vermelho area can be maintained at or close to its current capacity for the foreseeable future. Other model forecasts that include additional capacity indicate that the Pico Vermelho reservoir is likely to be capable of supporting an expansion in capacity that EDA Renováveis, S.A. is considering.

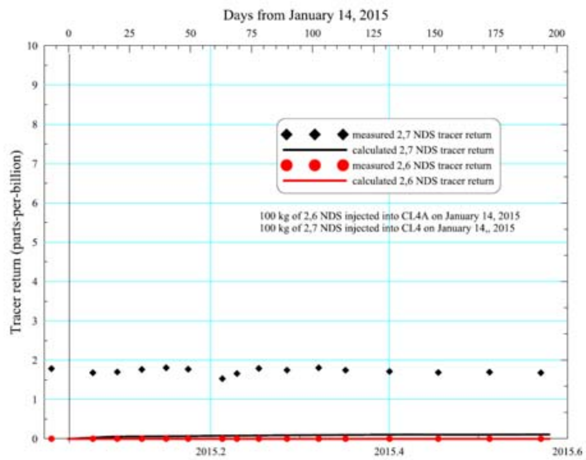

Figure 11: Tracer return matching at well CL6 (GeothermEx, 2016).

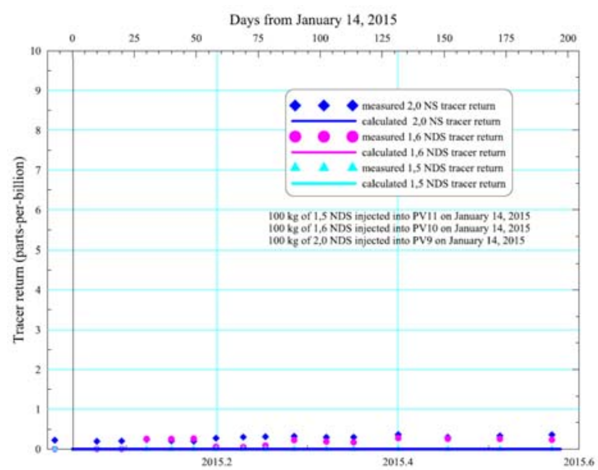

Figure 12: Tracer return matching at well PV7 (GeothermEx, 2016).

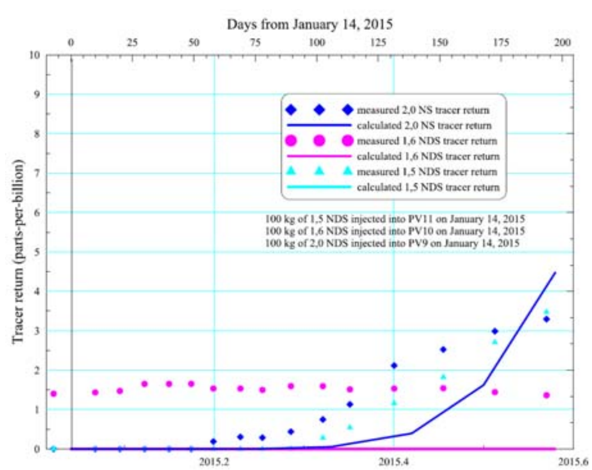

Figure 13: Tracer return matching at well PV8 (GeothermEx, 2016).

6. Conclusions

Comparison of the results of the 2015-2016 tracer test with the results of the 2007-2008 test indicates that in the Cachaços-Lombadas sector of the field, the speed and magnitude of the return of injected water from the injection wells to the production wells has not changed substantially from one testing period to the other. In general, the tracer returns appear to be a bit slower and weaker in the recent test than in the 2007 test, indicating that the allocation of some of the injection to CL4-A is reducing the rate of injection return somewhat. In the Pico Vermelho sector, the tracer returns in the 2015 test was substantially weaker than in the 2007 test, both in timing and magnitude. This result can be attributed directly to the relocation of injection from wells PV5 and PV6 to the more distant PV9, PV10 and PV11. In both sectors of the field, the current exploitation scheme appears suitable to sustain the present generation level for many years with minimal make-up drilling.

The overall tracer-test results (from both the 2007 and 2015 tests) tend to confirm the model of the Ribeira Grande field as a single, hydrologically connected geothermal reservoir, despite the variations in permeability mentioned above.

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REFERENCES

Axelsson, G. “Tracer tests in geothermal resource management.” EPJ Web of Conferences 50, 02001, 2013, 9 pp.

GeothermEx, a Schlumberger Company. “Update of the Conceptual and Numerical Model of the Ribeira Grande Geothermal Reservoir.” Report for EDA RENOVÁVEIS, S.A., 2016.

GeothermEx, Inc. “Update of the Conceptual and Numerical Model of the Ribeira Grande Geothermal Reservoir.” Report for SOGEO – Sociedade Geotérmica dos Açores, S.A., 2008.

Moore, R. “Geology of three late Quaternary stratovolcanoes on São Miguel, Azores.” USGS Bull. 1990, 1-26.

Pham, M., Klein, C., Ponte, C., Cabeças, R., Martins, R., and Rangel, G. “Production/Injection optimization using numerical modeling at Ribeira Grande, São Miguel, Azores, Portugal.” *Proceedings World Geothermal Congress*, Bali, Indonesia (2010), 25-29.

Ponte, C., Cabeças, R., Rangel, G., Martins, R., Klein, C., and Pham, M. “Conceptual Modeling and Tracer Testing at Ribeira Grande, São Miguel, Azores, Portugal.” *Proceedings World Geothermal Congress*, Bali, Indonesia (2010), 25-29.

Ponte, C., Cabeças, R., Martins, R., Rangel, G., Pham, M., and Klein, C. “Numerical Modeling for Resource Management at Ribeira Grande; São Miguel, Azores, Portugal.” *GRC Transactions*, Vol.33, (2009), 847-853.

Rose, P., Johnson, S., and Kilbourn, P. “Tracer Testing at Dixie Valley, Nevada, Using 2-Napthalene Sulfonate and 2,7-Naphthalene Disulfonate. Proceedings, Twenty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California (2001), 6 pp.

Simkin, T., Tilling, R. I., Vogt, P. R., Kirby, S. H., Kimberly, P. and Stewart, D. B. “This Dynamic Planet. Planet World Map of Volcanoes, Earthquakes, Impact Craters and Plate Tectonics.” USGS, Smithsonian Institution and U. S. Naval Research Institution, (2006).

Viveiros, F., Ferreira, T., Silva, C., Óskarsson, N., Hipólito, R. “Natural and anthropogenic influences on the gas geochemical monitoring at Fogo Volcano (São Miguel Island, Azores).” VOLUME project, EU PF6 (No. 018471), (2009), 299 - 308.

Wallenstein, N., Duncan, A. M., Chester, D. K., Marques, R. “Fogo Volcano (São Miguel, Azores): a hazardous landform.” Z. Geomorphol., 3, (2007), 259-270.