Geochemical monitoring and Tracer tests in the Reykjanes production field

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Keywords: Geochemical monitoring, Reykjanes, Chloride, Tracer test

ABSTRACT

Geochemical monitoring has been conducted in the Reykjanes field since the first production well was put online in 1970. It became more extensive after the commissioning of the 100 MWe powerplant in the spring of 2006 which dramatically increased the production of the field. In this paper chemical monitoring of the dissolved solids especially chloride in relation to the inter-well tracer tests conducted will be presented. The Cl concentrations since 2012 indicate that a boiling trend which was observed in previous years has stopped or reached an equilibrium, as Cl concentrations in wells have not increased although some fluctuations are seen. Nonetheless, the recent Cl concentrations from some of the wells are higher than the concentrations measured before commissioning of the power plant. Many of those wells have Cl concentration higher than that of seawater. Chloride concentrations in many wells have been decreasing in recent years. It is likely that the decreasing Cl concentrations in some of the wells may be attributed to dilution with the reinjected liquid. Tracer tests conducted in the field also confirm the feedback between the brine and condensate mixture re-injection and freshwater injection and the deep fluid chemical composition.

1. INTRODUCTION

The Reykjanes high temperature geothermal system is located on the Reykjanes Peninsula in SW Iceland. As of now 18 production wells are available in the area having reservoir temperatures ranging from about 270 to 310^{0}C. The thermal activity in the field is concentrated in small area having altered rocks, steam vents, mud pits and warm grounds. The reservoir fluid in the Reykjanes system is hydrothermally modified seawater with some addition of magmatic gases (Arnórsson,1978; Freedman et al., 2009; Hardardóttir et al., 2009). The first exploration well in Reykjanes was drilled to a depth of 162 m in 1956, yielding 3–4 kg/s of two-phase fluid at 185°C. Further exploration drilling followed in the late 1960s. The first proper production well, RN-8, was drilled in late 1969 and started producing in 1970. In the first years, RN-8 was the only production well. In 1983, well RN-9 was added which subsequently was replaced by production from well RN-12 which started in 2003. This development has been discussed in detail in reports by Bjarnason (2002) and Hjartarson and Júlíusson (2007). Apart from 1975–1978 when there was no production, the average annual production ranged from 40 to 80 kg/s until 2006. In the spring of 2006, the 100 MWe Reykjanes power plant was commissioned, thus dramatically increasing the production of the system.

2. TRACER TESTS

Seven inter-well tracer tests using naphthalene sulphonate compounds have been initiated in Reykjanes since 2013. The first test involved the injection of 75 kg of 2,7-naphthalene disulphonate (2,7-NDS) and 2000 L of methanol into well RN-20b on 12th August 2013, followed by continuous 140 kg/s re-injection until June 2014. The second test started on 10th January 2014 with the injection of 150 kg of 2-naphthalene sulphonate (2-NS) into well RN-33, followed by continuous 55 kg/s injection of cold fresh water for six months. These two tracers have been detected in many wells and calculated returns to date exceed 55% and 45%, respectively (Figures 1 and 2). The third tracer test was commenced on 27th May 2015 when 400 kg of 2,6-naphthalene disulphonate (2,6-NDS) were injected into well RN-34 followed by a continuous 55 kg/s injection of cold water and the fourth test started on 11th November 2015 with the injection of 275 kg of 1-naphtalene sulphonate (1-NS) into well RN-29, accompanied by a continuous 40 kg/s injection of condensate. No returns from these two tracer tests have been detected in the production wells. A fifth tracer test was initiated on 5th July 2016 with the injection of 400 kg of 2,7-NDS into well RN-30. Subsequently 30–45 kg/s of cold water was injected into the well for the first few days, but the amount was later reduced to 15–20 kg/s. A rapid recovery (< 10 days) of this tracer was observed in well RN-27. Consecutively 2-NS has also been detected in this well which could be probably due to thermal breakdown of 2,7-NDS. Due to the rapid returns, a sixth tracer test was carried out in well RN-30 with the injection of 175 kg of 1,6-naphthalene disulponate (1,6-NDS) into the well on 30th November 2016. The tracer was dissolved in 5 m^3 of cold water, but the tracer was not followed by continuous injection into the well. This compound was detected in wells RN-27 and RN-28 within two weeks, again in very high concentrations (>300 ppb) in well RN-27. However, as the analytical method cannot separate 1,6-NDS and 2,7-NDS in saline fluids well enough for quantification, the absolute concentration is not well constrained. The last tracer test was carried out on 12th April 2018 with the injection of 500 kg of 1-NS into well RN-15/IDDP-2 followed by continuous 12-15 kg/s of cold fresh water which was later replaced by injection of hot water. This tracer compound was not detected in any of the production wells to date.

Additionally, approximately 30 kg of SF6 were injected through the drill string into well RN-15/IDDP-2 on 9th December 2016. Steam samples were collected from several wells from the time of injection until March 2017, but no recovery has been detected. The lack of SF6 tracer recovery stems from either low mass of SF6 used for injection, possible problems during tracer injection, or too short monitoring period. However, the concentrations of atmospheric gases and changes in isotopic composition in well RN-12 shows the drilling fluid arrived to this well in the second half of 2016.

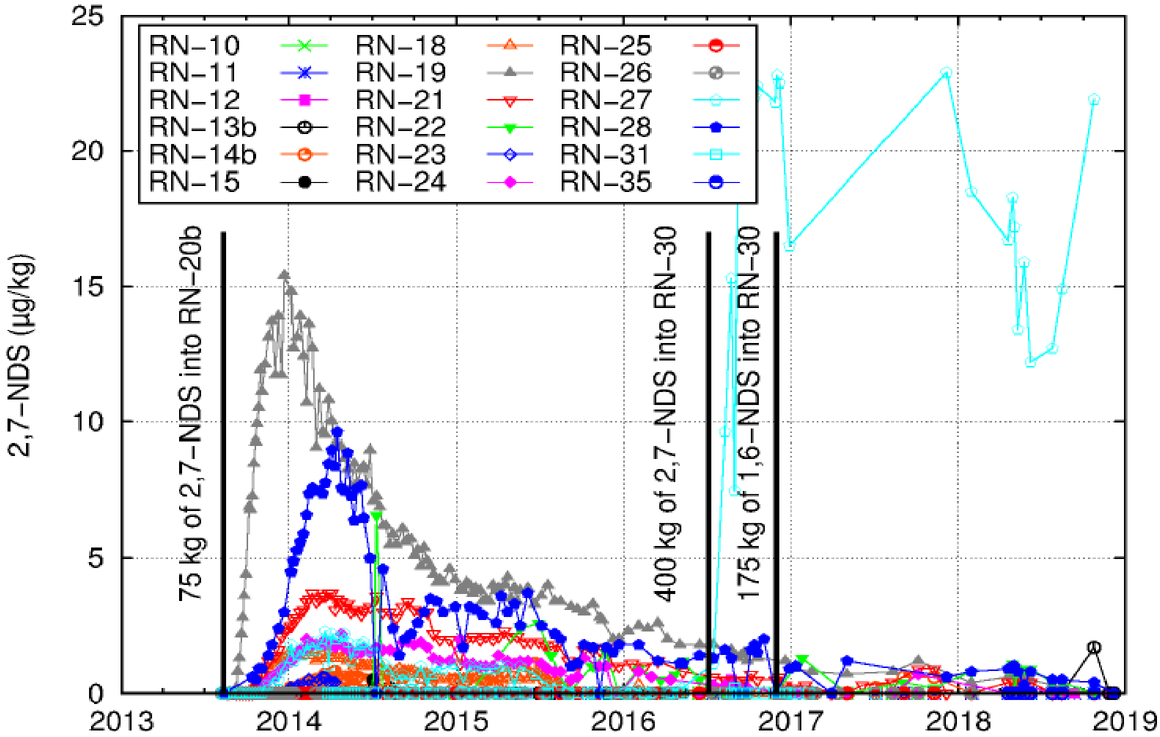

Figure 1: Concentration of 2,7-NDS in Reykjanes production wells, 2013–2018

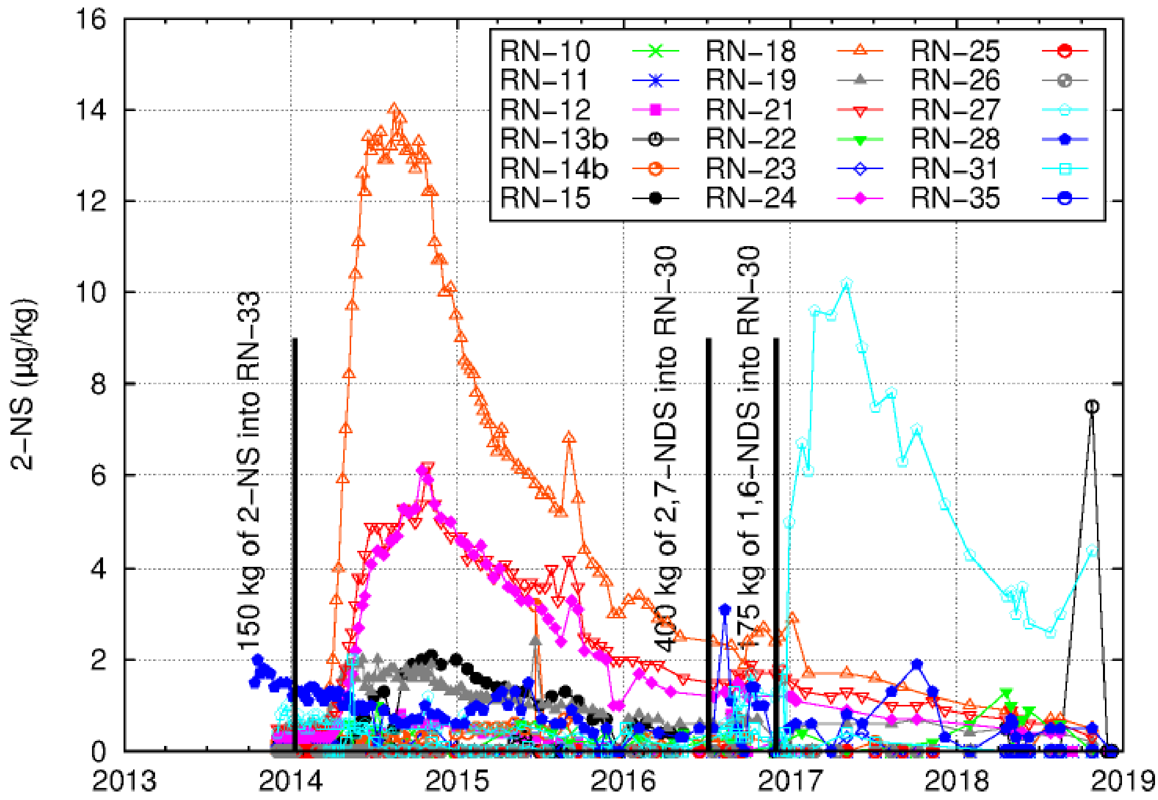

Figure 2: Concentration of 2-NS in Reykjanes production wells, 2013–2018

3. CHEMICAL MONITORING

Chemical changes in geothermal fields are observed by conducting chemical monitoring. In Reykjanes field geochemical monitoring has been conducted since the first production well was put online in 1970. It became more extensive and systematic after the commissioning of the 100 MWe powerplant in the spring of 2006. The monitoring program is conducted by sampling the wells twice a year (once after 2011) for liquid and steam samples. The samples are collected using webre separator connected to the well head. The water samples are cooled using a cooling spiral prior to sampling. pH, CO2, H2S and NH3 are determined from untreated samples, samples for analysis of SiO2 are diluted 1:10 upon collection, samples for determination of F, Cl, Br, B, TDS and stable isotopes are filtered through a 0.45 µm cellulose acetate membrane filter, SO4 is determined from a filtered sample in which H2S has been precipitated as ZnS, and the concentrations of metals and trace elements are determined from filtered samples which have been acidified with HNO3 (supra pure). Steam samples are collected to an evacuated double-port glass flask containing 50 mL of 40% NaOH. Upon entering the flask, the steam will condense and CO2 and H2S will dissolve in the caustic solution, but other gases will be collected into the head-space of the flask. Condensate samples are collected through a stainless steel cooling spiral immersed in cold water. A more detailed description of the sample collection and preservation protocol is given by Ármannsson and Ólafsson (2006). In addition to these in 2018 separate monthly samples for the analysis of chloride and silica have also been collected from all the wells.

4. CHLORIDE CONCENTRATION IN THE WELLS AND TRACER TESTS

The Cl concentrations since 2012 indicate that a boiling trend which was observed in previous years has stopped or reached an equilibrium, as Cl concentrations in wells have not increased although some fluctuations are seen. Chloride concentrations in some wells, some of which had previously shown indications of boiling, have been decreasing in recent years. This includes wells RN-11, RN-12, RN-14b, RN-18, RN-19, RN-21, RN-22, and RN-24. This trend in some of the wells (RN-14b, RN-15, RN-18, RN-19, RN-21 and RN-24) is attributed to dilution with the reinjected liquid, as the tracers injected into RN-20b in 2013 and into RN-33 in 2014 have been measured in these production wells confirming the connection between the brine and condensate reinjection and/or freshwater injection, and the deep fluid chemical composition. RN-12 has shown a decrease in Cl concentration. This decrease in Cl concentration which have not shown major tracer recovery in late 2016 and 2017 was probably caused by drilling fluids used during the deepening and drilling of RN-15/IDDP-2. In 2018 the Cl concentration in this well increased suggesting that there is no longer substantial inflow of dilute fluids into this well.

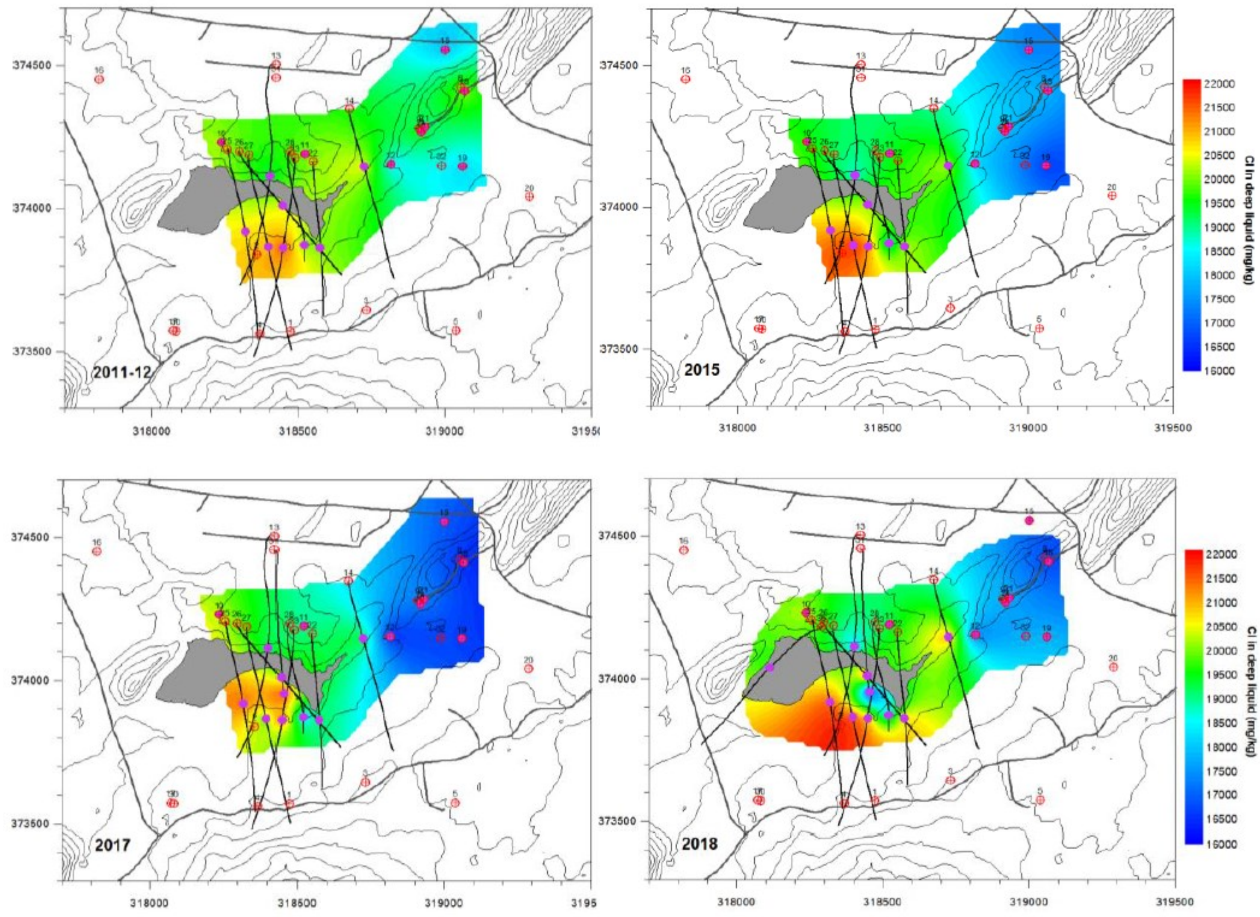

Figure 3: Distribution of deep liquid chloride concentration in 2011-12, 2015, 2017 and 2018.

Figure above shows the calculated distribution of Cl concentrations in the deep liquid in 2011–2012, 2015, 2017, and 2018, bridged by a Kriging algorithm. Each data point (purple dots) is the annual average value of Cl in the deep liquid, plotted at the location of the main aquifer in each well, or at the average depth of aquifers in case of wells with two or more large aquifers. In most cases, the values are averages of two samples collected in that particular year, except in 2018 when only one sample was collected from each well. The effect of injection and reinjection into RN-20b and RN-33 is progressing from the east to west until 2017. This effect was possibly magnified by the freshwater inflow into RN-15/IDDP-2 during drilling operations in late 2016. This trend has stopped or even reversed in 2018. As can be seen, lower Cl concentration area (<18500 mg/kg; blue) decreased in 2018 and at the same time higher Cl concentration area (>21500 mg/kg; red) in the southern part of the area increased, mainly due to the recovery of well RN-27 from effects of injection into well RN-30. Wells RN-25 and RN-26 in the southwestern part remain largely unaffected by reinjection (Galeczka et al.2019). The tracer returns for those tests which gave returns in relation to the chloride concentration in the production wells will be described below.

4.1 Tracer test 1

The first tracer test involved the injection of 75 kg of 2,7-naphthalene disulphonate (2,7-NDS) and 2000 L of methanol into well RN-20b on 12th August 2013, followed by continuous 140 kg/s re-injection until June 2014. A significant recovery was observed in well RN-19 in 25 days after injection revealing a strong connection with the injection well. In addition to this RN-27 and RN-28 has also given returns from this test. The other well which showed even stronger connection with the injection well than RN-19 is well RN-32. This well was opened for discharge on 20 March 2014 after one year of warm up. While this well was discharging samples were collected from the well for analysis of the tracer compound 2.7-naphthalene disulphonate. The tracer was detected in all samples, generally in slightly higher concentrations than in samples collected from RN-19 on the same days. This suggests that the fluid produced from RN-32 is to a considerable extent reinjected liquid from RN-20b and furthermore suggests that the flow connection between RN-20b and RN-32 may be even stronger than that between RN-20b and RN-19. The Cl concentration in well RN-32 during discharge was also quite low, and similar to what has been observed in the samples from nearby well RN-19, where Cl concentrations have dropped considerably almost certainly due to reinjection into RN-20b (Gylfadóttir et. al 2014). The connection between the injection well and wells RN-27 and RN-28 which gave clear tracer returns was clearly depicted during the course of monthly sampling when RN-32 was discharged again for a test in early September of 2018 (Figure 4). As can be seen from the figure after one month of continuous discharge well RN-28 become dry as its raw chloride content coupled with conductivity and silica plummeted to very low values. After the second month a decrease in all these parameters was observed in well RN-27 implying a very good corroboration between the tracer returns and the chloride concentrations in the wells.

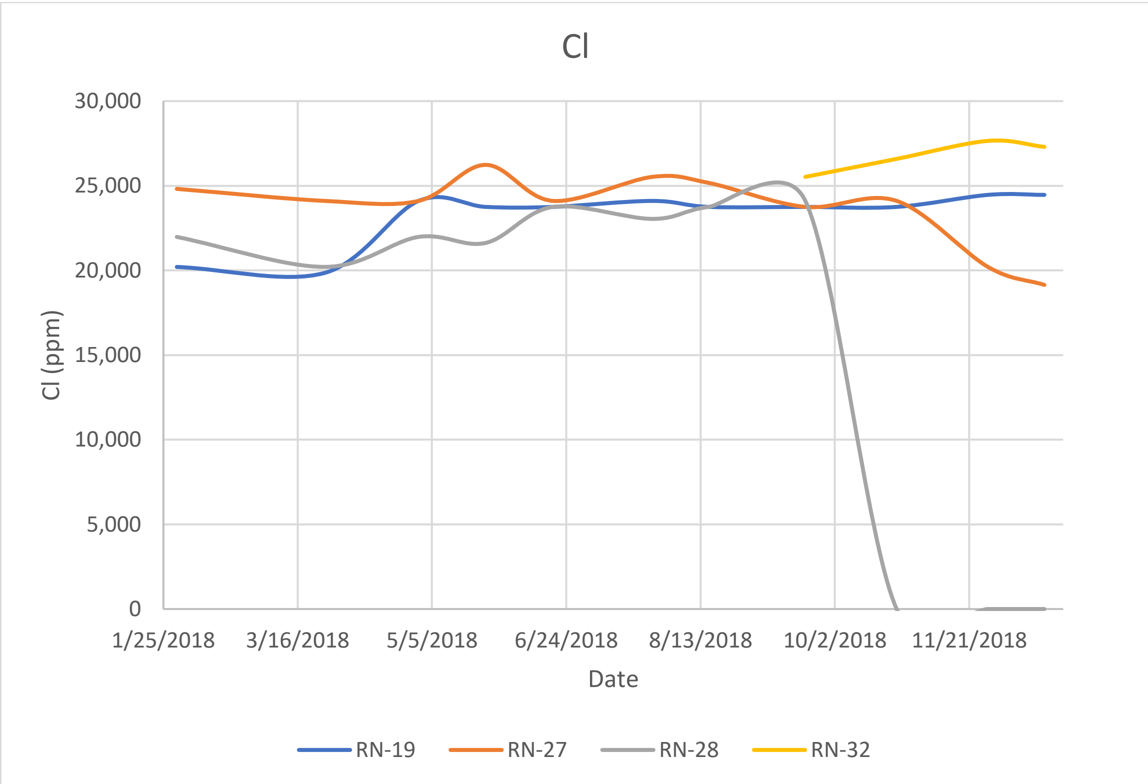

Figure 4: Well head chloride concentration in 2018 in selected wells.

4.2 Tracer test 2

The second test started on 10th January 2014 with the injection of 150 kg of 2-naphthalene sulphonate (2-NS) into well RN-33, followed by continuous 55 kg/s injection of cold fresh water for six months. The tracer test shows this well to be connected with production well RN-18 with the first sign of return 64 days after injection. Cl concentrations in wells RN-18, RN-21 and RN-24 which had previously shown indications of boiling were observed to decrease subsequently becoming significantly lower than seawater salinity. The decrease is related to the influence of reinjected liquid in well RN-33. Wells RN-21 and RN-24 have also connectivity with RN-33 giving a return after 77 days and 84 days of injection respectively.

5. CONCLUSION

Different tracer tests have been conducted to explore the different pathways and the hydrological system of the reservoir. These tests have shown a good connectivity between the production and injection wells which have also been confirmed by the decreasing chloride concentration results. The connection between the injection well RN-20b and wells RN-27 and 28 which gave clear tracer returns was clearly depicted during the course of monthly chloride sampling when RN-32 was discharged again for a test in early

September of 2018. The chloride and tracer test results have given invaluable information regarding the connectivity of the wells in the Reykjanes geothermal field.

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