GEOCHEMICAL RESPONSE OF THE ROTOKAWA RESERVOIR TO THE FIRST 5 YEARS OF NGA AWA PURUA PRODUCTION

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Keywords: *Rotokawa, geochemistry, Nga Awa Purua, dilution, silica, boiling, production*

ABSTRACT

Best practice field management requires identification of the key processes acting within the reservoir and understanding of the relationships between reservoir and process chemistry changes with the potential to impact resource and infrastructure sustainability. Following the initial development of the 34MWe Rotokawa Geothermal Power Station, the Rotokawa reservoir exhibited relatively stable production geochemistry characteristics. In 2010 the 138MWe Nga Awa Purua Geothermal Power Station (a joint-venture between Mighty River Power and Tauhara North No.2 Trust) was commissioned which increased steam production and brine injection in the Rotokawa reservoir. As anticipated, this generated a number of transient hydrogeologic changes in the reservoir which were monitored closely through regular Tracer Flow Testing (TFT), produced fluid geochemistry sampling, in addition to a variety of other reservoir testing activities. When integrated and evaluated within a geoscientific context, these data provide important insights into both transient and long-term reservoir changes which can occur in response to operational activities. This paper will discuss the geochemical response of the Rotokawa reservoir to Nga Awa Purua start-up and operation over the last 5 years. Production well geochemistry has identified three main geochemical responses within the reservoir: boiling, injection returns and dilution from marginal recharge. In addition, a transient increase in silica within the production fluids was identified that has stabilised over the last two years to levels which do not impact operational activities.

1. INTRODUCTION

The Rotokawa geothermal field is located within the Taupo Volcanic Zone (TVZ). In 1997 the Rotokawa geothermal power station was commissioned, initially a 24 MWe Ormat Geothermal Combined Cycle plant which was expanded by 10 MWe to 34 MWe in 2003. In 2010 the triple-flash 138 MWe Nga Awa Purua geothermal power station was commissioned.

Since production started from Rotokawa there has been significant learning and development of the conceptual understanding of the chemistry in the field. This has identified three key processes: injection returns, boiling and marginal recharge. This paper will discuss geochemical observations and the identification of these processes.

This paper forms part of a series of papers celebrating 5-years of Nga Awa Purua generation. Associated papers include: an update on the conceptual model by Sewell *et al.* (2015a); an update on the pressure, temperature and enthalpy by Hernandez *et al.* (2015a); a summary of tracer tests conducted on the field by Addison *et al.* (2015a); and, a paper on the steamfield configuration by Hoepfinger *et al.* (2015). A recent review paper by McNamara *et al.* (2015) summarises most of the historical geoscience work on the Rotokawa field.

A simplified configuration of production wells as of 2015 is shown in Figure 1, indicating what power plant each well feeds. The Rotokawa geothermal field layout is shown in Figure 2. The interconnection from the RK32-33-34 production pad enables each well to feed either Nga Awa Purua or Rotokawa. Since the interconnection of this well pad to the Rotokawa power station in 2013 (Hoepfinger *et al.*, 2015), RK32 has predominantly supplied the Rotokawa power station, with RK33 and RK34 supplying Nga Awa Purua.

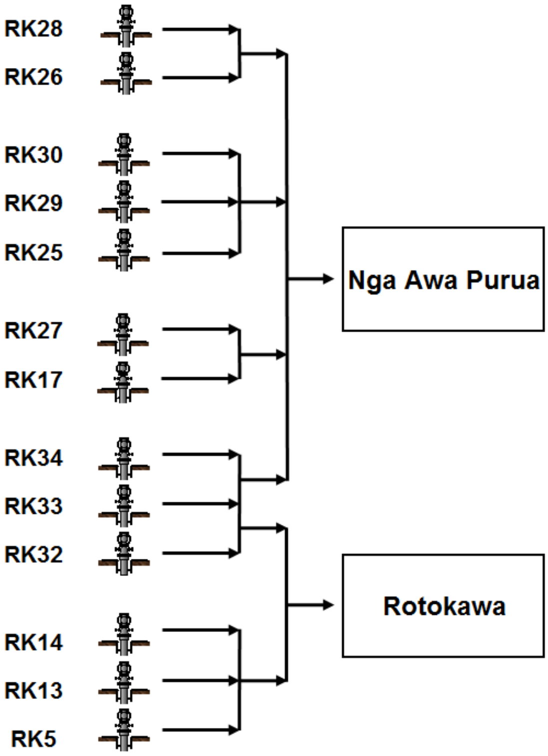

Figure 1: Production configuration for the Rotokawa Geothermal Field as of 2015

Three different injectate fluids are generated on the Rotokawa field. The first is a combined condensate and brine from the Rotokawa power station (700-720 ppm SiO_2, ~165˚C, Silica Saturation Index [SSI] ~1.0, pH_{25} ~5.1). The Nga Awa Purua power station makes use of a direct-contact condenser, therefore the condensate (0 ppm SiO_2, ~45˚C, pH_{25} ~7) is oxygenated and is injected separately from the brine (~1150 ppm SiO_2, ~130˚C, SSI 2.3, pH_{25} 5.0). Thus Nga Awa Purua power station generates two different injectate fluids. As of 2015 there are five deep injection wells in the South East of the field and two intermediate aquifer injection wells (300-500m depth).

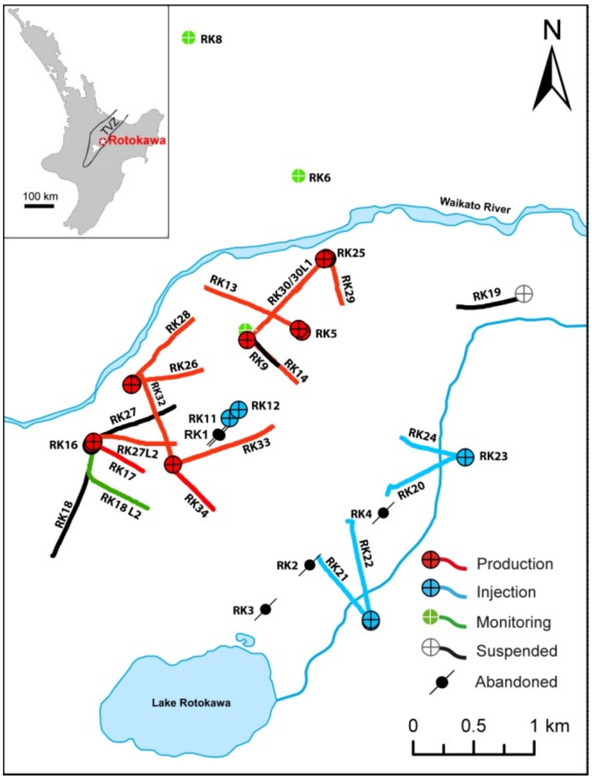

Figure 2: Rotokawa Geothermal field layout as at 2015

2. NATURAL STATE

The natural state chemistry for the Rotokawa geothermal field is given in Winick *et al.* (2011) and in Hedenquist *et al.* (1988).

Significant gradients were observed across the field from southeast to northwest, in terms of Cl, Cl/B, Na-K-Ca geothermometry and non-condensable gases. These trends tend to be perpendicular to the main NE-SW structural axis of the production field and the wider TVZ.

It was assumed that prior to deep injection in RK13 (December 2004) discharges from deep wells RK1, RK4, RK5, RK6, RK9, RK13 and RK14 were representative of natural-state reservoir conditions.

The main hot, deep, upflow is thought to be in the south of the field. This rises and boils, outflowing from the system towards the north. Progressive dilution along the outflow by cooler marginal fluids is largely responsible for the observed gradients in chemistry, in addition to fluid-rock interactions along the pathway. A large structural feature (the Central Field Fault) in the centre of the field provides a zone of enhanced vertical permeability, allowing deep reservoir fluids to rise and boil within the intermediate aquifer. The intermediate aquifer is a complex mixture of gas-rich steam condensates, groundwater, boiled reservoir fluids, and acid-SO_4-Cl fluids from a shallow, steam-heated aquifer in the vicinity of Lake Rotokawa.

3. PRODUCTION CHEMISTRY OBSERVATIONS

Sampling Program

Tracer flow testing and geochemistry sampling for both steam and brine is conducted every 2-3 months for each production well. Tracer flow testing provides data on steam and brine flows at a given wellhead pressure and collection pressure. This data is used to determine the enthalpy of the total discharge. Brine geochemical analytes are: pH, conductivity, total inorganic carbon (these are speciated), Cl, F, SO_4, sulfide (as H_2S), As, B, Ca, Fe, Li, Mg, K, Na, NH_3, Rb, SiO_2. Steam geochemical analytes are: CO_2, H_2S, CH_4, H_2, N_2, NH_3, He, O_2, Ar.

Chemistry sampling at the Nga Awa Purua power station is conducted monthly, with brine sampled after the HP, IP and LP separators. HP steam, IP steam and LP steam are sampled for gas as part of the emissions trading scheme reporting. The Rotokawa power station is sampled approximately every two months, with the injectate sampled for brine chemistry. Steam and condensate are also sampled as part of the emissions trading scheme.

Sulfate

Sulfuric acid (98%) is used to inhibit silica polymerisation at Nga Awa Purua. Addition of sulfuric acid to HP brine is conducted to enable additional energy extraction during the IP and LP flash with further details given in Addison *et al.* (2015b). Since the start-up of Nga Awa Purua, there has been a continual decrease in the quantity of sulfuric acid required to achieve a pH_{25} set-point of 5.0 in the LP brine, as the titration curve has had a reduction in buffering due to lower bicarbonate production. Due to this reduction in acid addition, from ~1.4 l/min in 2010 to ~0.8 l/min in 2015, the concentration of sulfate in the LP brine has reduced from around 130-140 ppm to ~100 ppm, as shown in Figure 3. No corresponding increase in sulfate in the produced fluids (HP brine) has been identified, with wells with confirmed injection returns, such as RK29, showing a decrease with time.

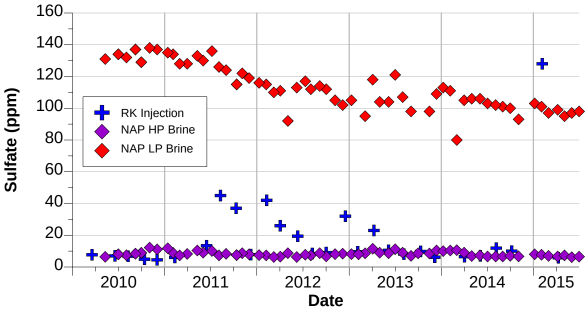

Figure 3: Sulfate results for the period 2010-present for Nga Awa Purua (HP brine & LP brine) and the Rotokawa Injectate

Maps of sulfate for 2010, 2012 and 2015 are given in Figure 10. These indicate that following start-up of Nga Awa Purua an increase in sulfate has taken place in the North-West wells with the highest values seen in RK28, then RK13 and RK26. All other production wells have seen a decrease in sulfate with time. In particular, a decrease in sulfate has occurred in the South-East of the production area (RK29, RK14, RK33) with these wells being nearest to the injection wells and having confirmed tracer test returns (Addison *et al.*, 2015a), indicating a total loss of sulfate as the injectate returns to production. This is significantly different to

Kawerau, another Mighty River Power operated plant making use of sulfuric acid dosing for silica management, where sulfate is continuing to rise in production wells and has been associated with injection returns.

Chloride

The Nga Awa Purua power station makes use of steam condensate for the make-up source for its evaporative cooling tower, therefore resulting in a mass difference between production and injection.

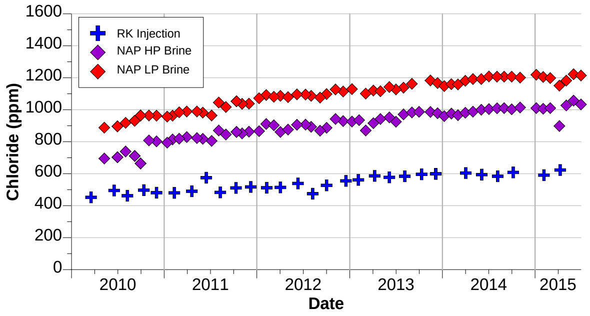

Figure 4: Chloride results for the period 2010-present for Nga Awa Purua (HP brine & LP brine) and the Rotokawa Injectate

The increase in chloride in the produced fluids to both power stations has been associated with a combination of injection returns from Nga Awa Purua brine and/or boiling. This will be discussed later in this paper. Marginal recharge is understood to also be playing a part in the field, with dilution seen in the North-West wells (RK28, RK26, RK13) which also have seen a higher sulfate fluid come in. Chloride maps for 2010, 2012 and 2015 are shown in Figure 12. This indicates that the North-West wells are likely drawing in a low chloride, high sulfate marginal recharge.

In 2010 the production area exhibited an approximate 200 ppm chloride gradient across the field. By 2015 this chloride gradient was over 600 ppm, with the highest levels seen in the South-Western well RK17 and the lowest value seen was in RK28, however this well has not been flowed since mid-2014. Chloride/Boron maps for 2010, 2012 and 2015 are shown in Figure 13. A continued gradient across the field continues from natural state, however since 2010 higher values have been observed in the South-Western wells (RK17, RK27) which has been associated with boiling and lower values have been observed in the North-Western wells (RK28, RK26, RK13) associated with dilution.

Gases

Calculated discharge quantities of CO_2 and H_2S are shown in Figure 5. Details on gas discharge monitoring are given in Lawson & Siega (2015). Upon start-up of Nga Awa Purua in early 2010 gas discharges increased significantly for the field. With time there has been downward trends for both CO_2 and H_2S (Figure 5). The CO_2:H_2S ratio of gas discharges for the Rotokawa field has also been declining, consistent with overall pressure drawdown and subsequent boiling in the field, in addition to injection returns.

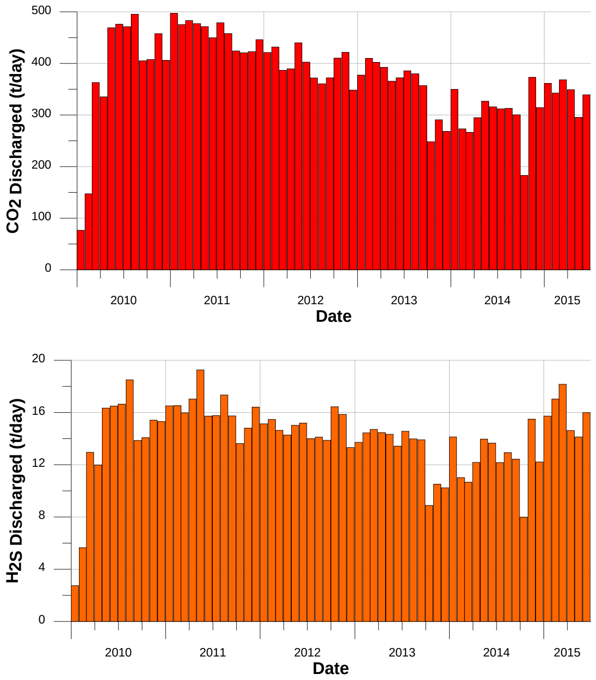

Figure 5: Calculated discharges per month from 2010 - mid-2015 for the Rotokawa Field for CO_2 (top) and H_2S (bottom)

Maps of gas in total discharge for 2010, 2012 and 2015 are shown in Figure 14. In natural state a general gradient across the field was seen. Under production a lower-gas is seen in North-Western wells (RK28, RK26) associated with marginal recharge, and lower-gas is seen in wells in the East of the production area (RK29, RK5, RK14) associated with injection returns. In 2015 a general SE-NW gradient across the field is still seen, with RK34 having the highest values at >1.4%.

Maps of the CO_2/H_2S ratios for 2010, 2012 and 2015 are shown in Figure 15. Overall the maps correlate very similarly to the pressure-drawdown within the field (Hernandez *et al.*, 2015a; Sewell *et al*, 2015a). With pressure drawdown and boiling within the Western wells (RK17, RK27, RK32), there has been a decrease in the CO_2/H_2S ratio. Early indications from RK34, which began production in early 2015, show that it is also seeing pressure drawdown based on its CO_2/H_2S values, however this may be due to a significant contribution from shallower boiling feed zones for this well.

Silica

The Nga Awa Purua station separates HP steam from brine through a vertical separator, with the brine then acid-dosed for an LP brine pH_{25} set-point of 5.0. This brine is then further flashed through two additional stages (IP and LP). The brine injectate has a silica concentration of ~450 ppm higher than the average production reservoir condition. Further details on silica management for Nga Awa Purua is given in Addison *et al.* (2015b).

The Rotokawa station separates steam from brine through a vertical separator. Steam flows to either the non-condensing turbine or through the OEC21 vaporiser. Following the non-condensing turbine this then flows through either OEC11 or OEC12. Brine is used through OEC1, through both the vaporiser and preheater, and is also mixed with steam condensate from OEC21 vaporiser and this then goes through the preheater on OEC21. The outlet fluids from OEC1 and OEC21 are then mixed with the steam condensate from OEC11 and OEC12 and then injected. This injectate has a SSI of 1.00 – 1.05 and is slightly lower in silica concentration than the production reservoir condition due to the production wells feeding the station having some excess enthalpy.

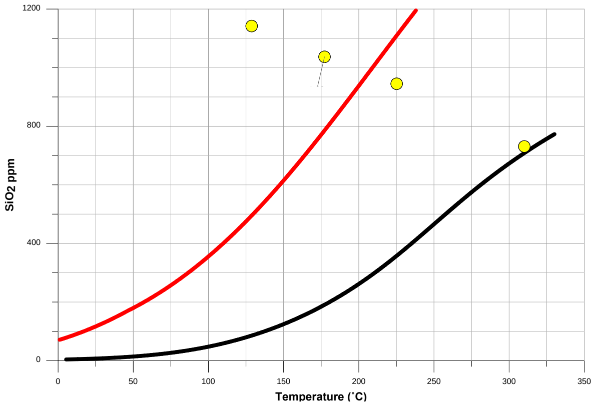

Figure 6: Nga Awa Purua Power Station shown on a silica concentration vs. temperature plot with various solubility trends. SSI values are provided relative to pure amorphous silica solubility as discussed in Addison *et al.* (2015b)

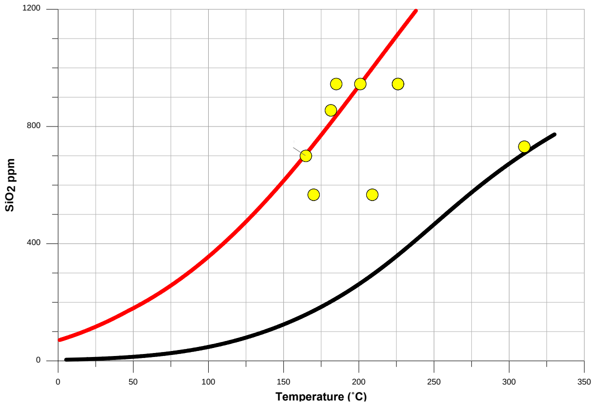

Figure 7: Rotokawa Power Station shown on a silica concentration vs. temperature plot with various solubility trends. SSI values are provided relative to pure amorphous silica solubility as discussed in Addison *et al.* (2015b)

Towards the end of 2012, following start-up of Nga Awa Purua in mid-2010, an increasing trend in silica concentration was observed in the combined fluids coming to Nga Awa Purua (Figure 8). With chloride increases suspected to be due to both boiling and injection returns, this possibly indicated that the produced fluids were not in full equilibrium with quartz. From 2013 to 2015 silica values have been stable and have shown signs of reducing. In early 2015 the previous method of taking a filtered-acidified sample was replaced with taking a filtered-diluted sample, with a 1:10 dilution ratio, as it was found re-analysis of the previous samples was not consistent or reliable as the samples were significantly over-saturated.

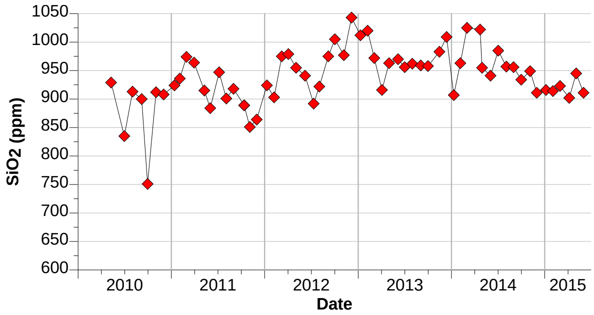

Figure 8: Nga Awa Purua HP Brine Monthly Silica Values

External Casing Corrosion

Both carbonic and sulfuric fluids have long been identified at Rotokawa previously (Winick *et al.*, 2011). Rising, boiling fluids insert quantities of CO_2 and H_2S into steam condensates that are formed within the intermediate and shallow aquifers. Carbonic fluids are considered to be the dominant corrosive fluid, with sulfuric fluids being localized where shallow fluids percolate down.

Casing integrity is monitored through regular High Temperature Casing Condition downhole logs (HTCC), with wells generally monitored every two-years, or longer if monitoring hasn't shown any external metal loss with time. Individual occurrences of identified corrosion or external metal loss is shown in Figure 9. These individual zones are typically 1-5m in thickness. This highlights that >75% of corrosion zones at Rotokawa occur within 200-600m depth.

Mitigation of external casing corrosion is conducted through a combination of injection of near–neutral fluids into the intermediate aquifer and through the use of corrosion-resistant cements. Corrosion-resistant alloy casing is planned to be used for repairing wells with external corrosion and also for the production casing of future wells when appropriate.

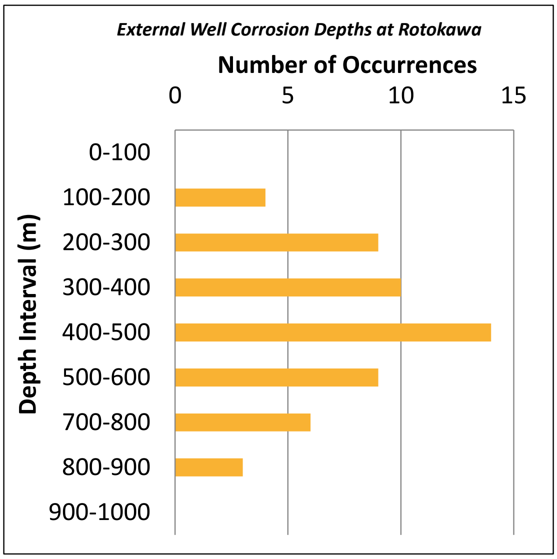

Figure 9: Individual occurrences of external metal loss zones with depth (from surface) at Rotokawa identified through HTCC logs. N.B. these are discrete occurrences where a well can have more than one occurrence in the depth interval, therefore not the number of wells with corrosion at that depth interval.

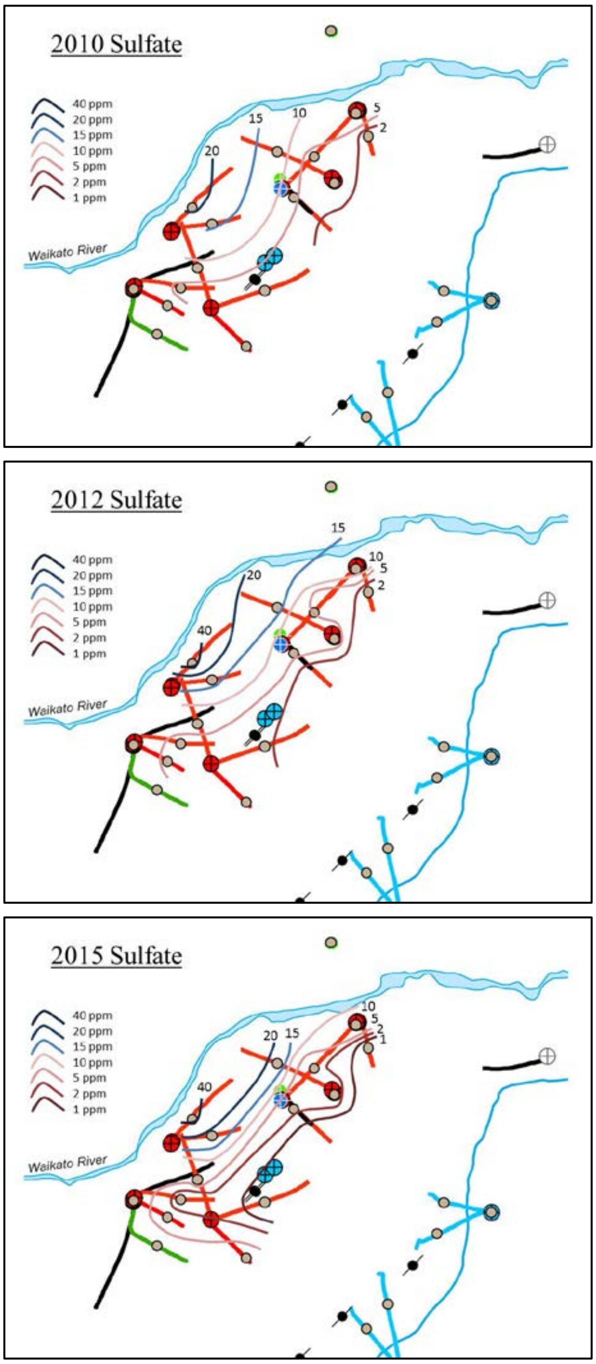

Figure 10: Reservoir Sulfate for 2010, 2012 and 2015. Grey circles shown indicate pressure pivot points for wells where this has been identified. N.B. For 2010 RK32, RK33 and RK34 were not drilled therefore these wells are not included. For 2012 RK34 was not drilled therefore this well was not included.

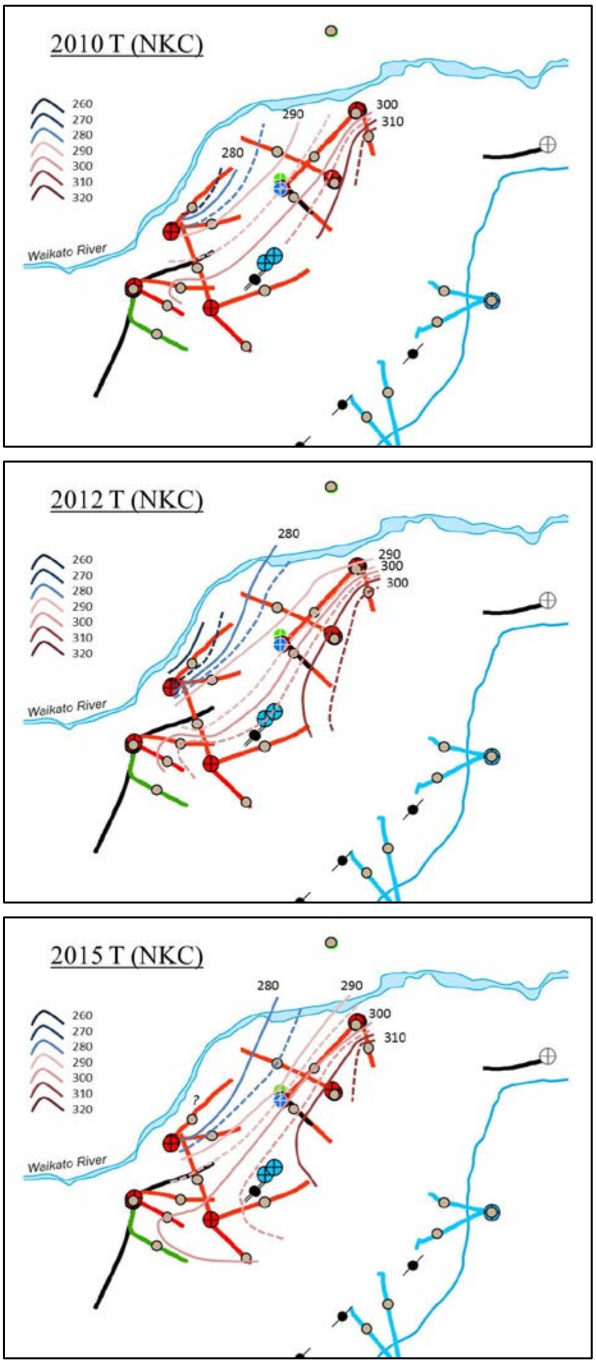

Figure 11: NKC Geothermometry Temperature for 2010, 2012 and 2015

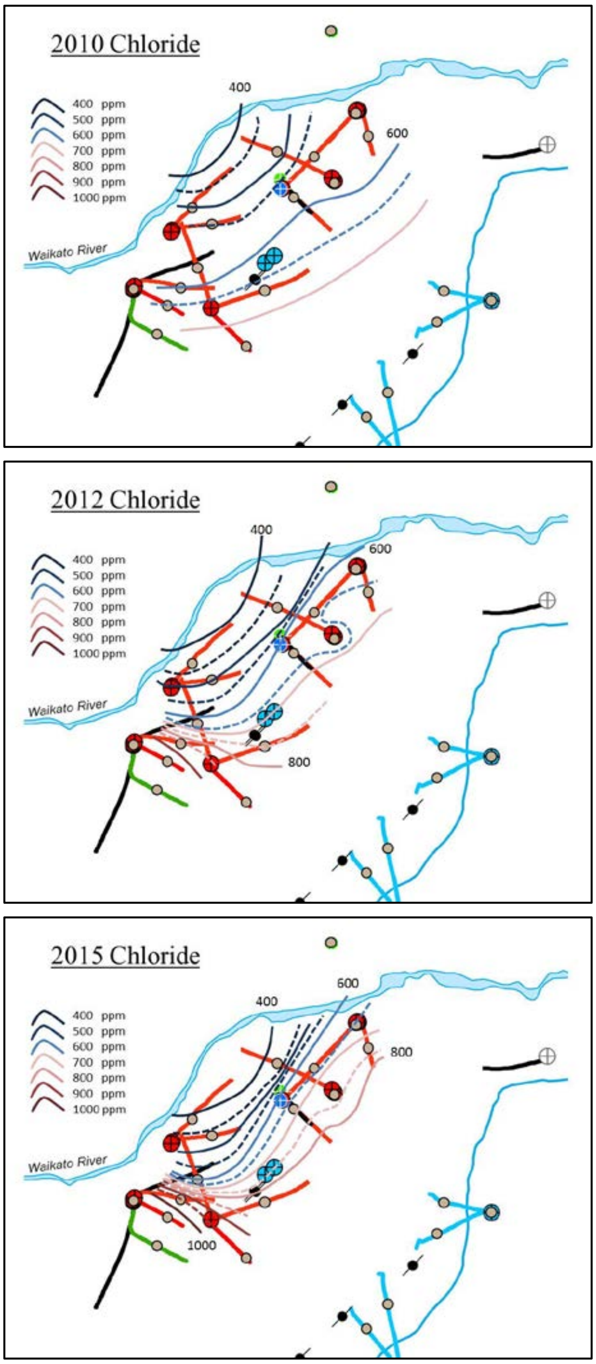

Figure 12: Reservoir Chloride for 2010, 2012 and 2015. Dashed contour lines represent the 50ppm interval between each 100ppm contour.

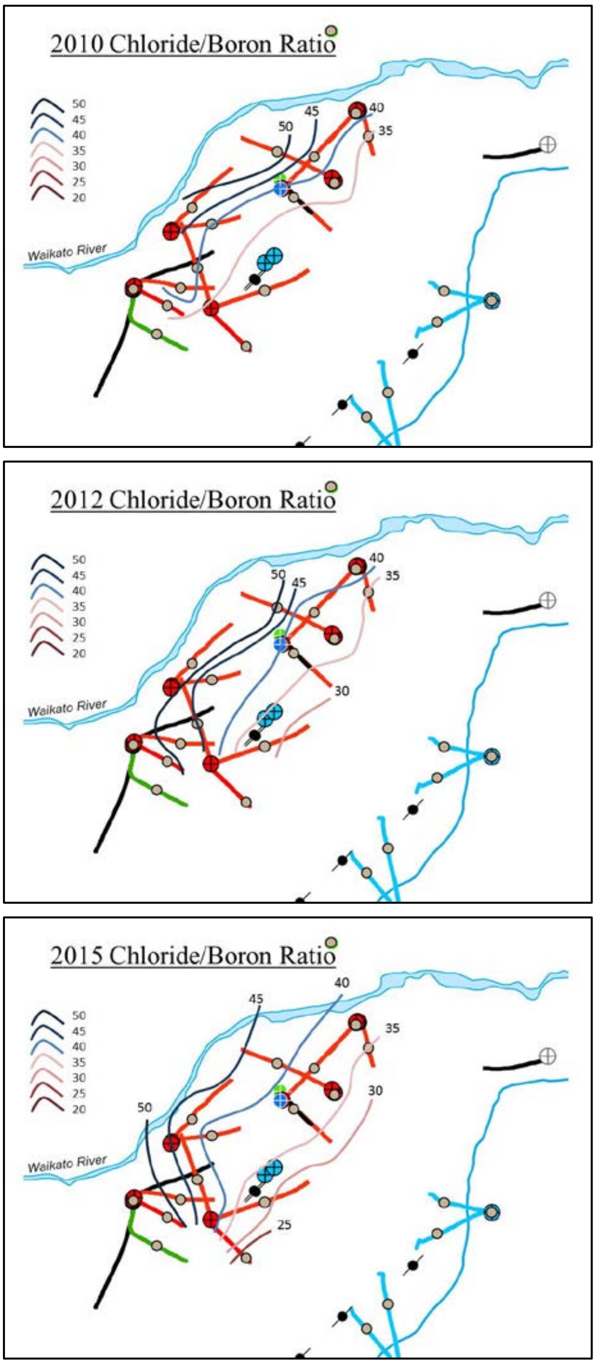

Figure 13: Reservoir Chloride/Boron ratios for 2010, 2012 and 2015.

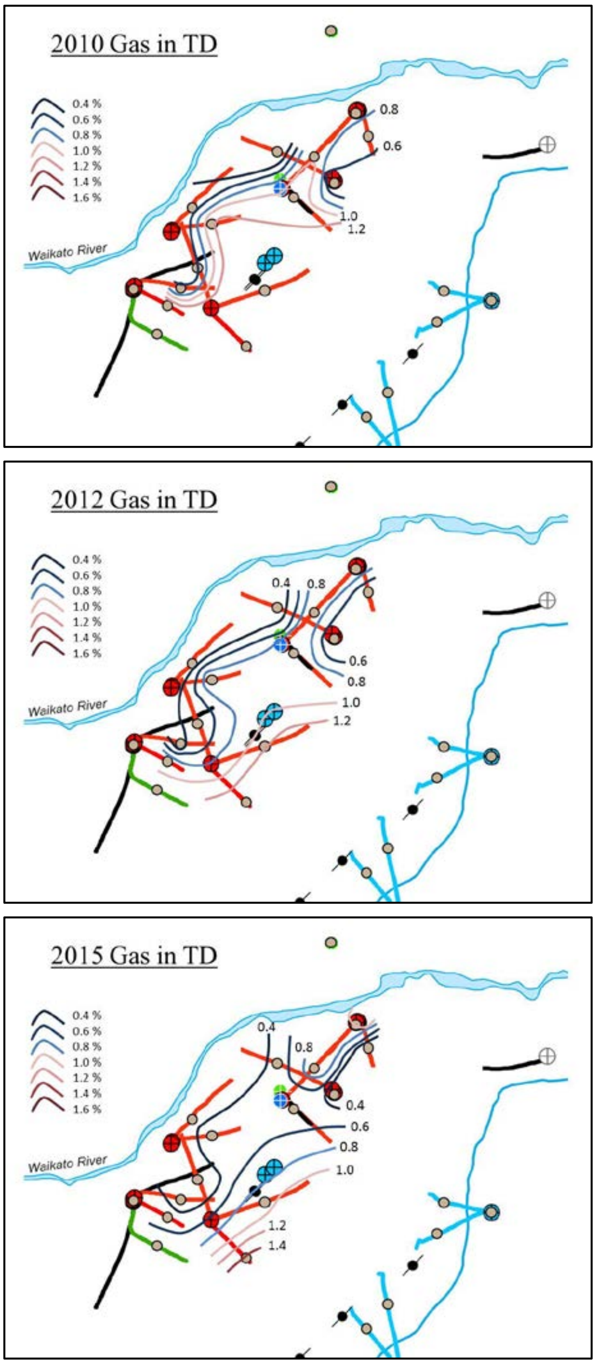

Figure 14: Gas in Total Discharge for 2010, 2012 and 2015.

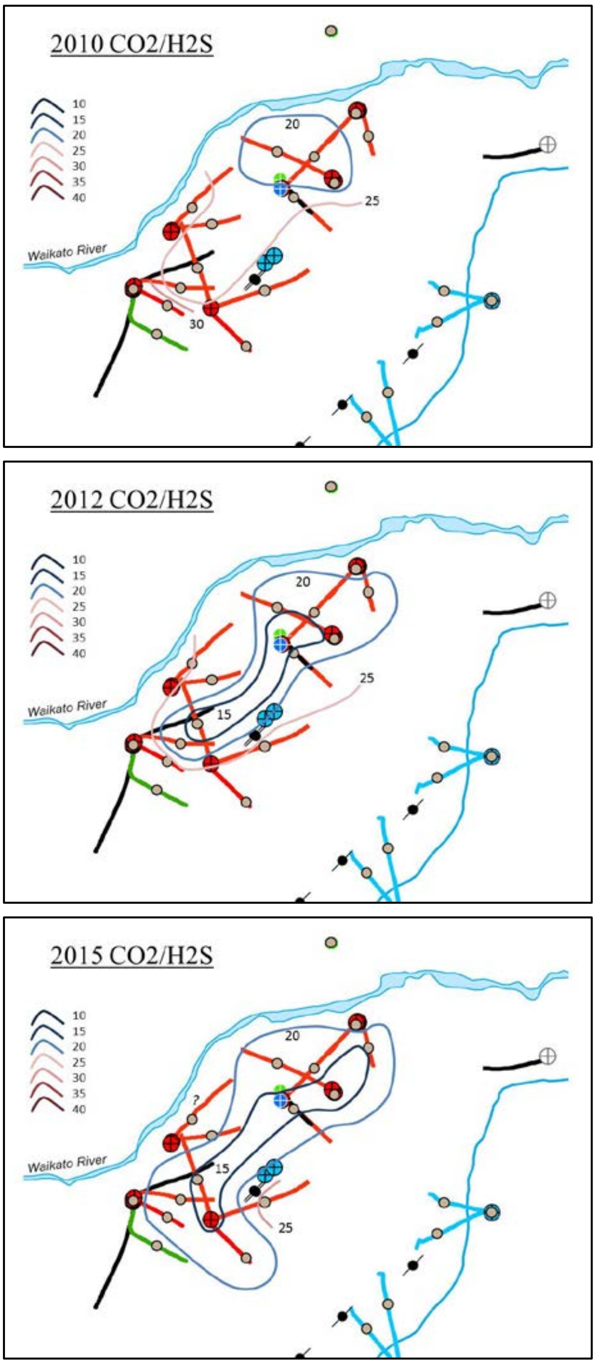

Figure 15: CO_2/H_2S ratio for 2010, 2012 and 2015.

4. OVERALL TRENDS OBSERVED

The dominant geochemical process for each area of production area is shown in Figure 16. The blue dashed area incorporates wells RK5, RK14, RK29 and RK33, representing the area of injection returns. The green dashed area incorporates wells RK17 and RK27, representing the area of boiling. The orange dashed area incorporates wells RK13, RK26 and RK28, representing the area of marginal recharge.

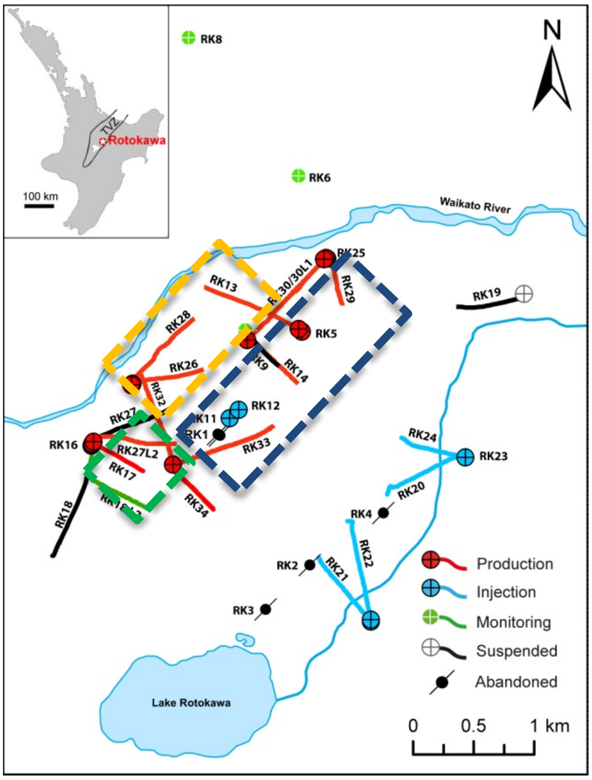

Figure 16: Map of Rotokawa Field showing key geochemical processes by area. Dashed blue indicated injection returns. Dashed green indicates boiling. Dashed orange indicates marginal recharge.

Wells RK25 and RK30 have generally been stable in their chemistry, indicating they are seeing a combination of processes or alternatively are within a compartment that does not see changes. RK32 is also generally stable in its chemistry, likely due to seeing a combination of marginal recharge and boiling. RK34 has only been flowing since early-2015.

Injection Returns

When Nga Awa Purua was started brine from the station was injected into RK21. In late-2010 brine injection was switched across to RK24. After this switch a chloride response was observed in wells RK5, RK14, RK29 and RK33 in addition to a pressure response (Quinao *et al.*, 2013). These wells have continued to see a chloride increase with time as shown in Figure 17.

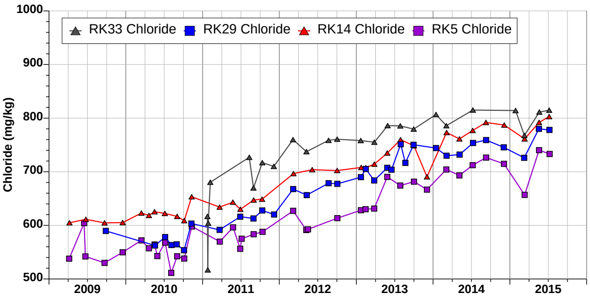

Figure 17: Chloride values for wells RK5, RK14, RK29 and RK33

From the latest reservoir tracer test, conducted in 2013, there were confirmed returns, with most returns to RK29 and then to RK14 (Addison *et al.*, 2015a). Whilst RK33 has the highest level of chloride within the wells on the Eastern side of the production area, it had the lowest levels of injection returns within these wells. It is likely that RK33 is also seeing either an influence of either boiling, and/or support from a high chloride source such as previous RK21 injectate or up-flow. Due to fluid temperatures at Rotokawa, many reservoir tracers used elsewhere breakdown on their way back to production. The use of ^{125}I, or other temperature stable tracers, will continue to be important for tracing injection returns at Rotokawa in the future.

The most significant case of pressure support and injection returns from RK24 is to RK29, which has a capacity of over 600 t/hr and since production this well has seen only a 5 bar reduction in pressure compared to the natural state (Hernandez *et al.*, 2015a). The chemistry of RK29 is shown in Figure 18, where an increase in chloride is seen and a decrease in sulfate, gas in steam and gas in total discharge. Both temperatures from geothermometry and measured downhole temperatures show that the fluid to RK29 is being reheated on its flow-path to the well, with liquid temperatures around 325-330˚C based on geothermometry. This is demonstrated in Figure 11 with NKC temperatures from 2010, 2012 and 2015 mapped.

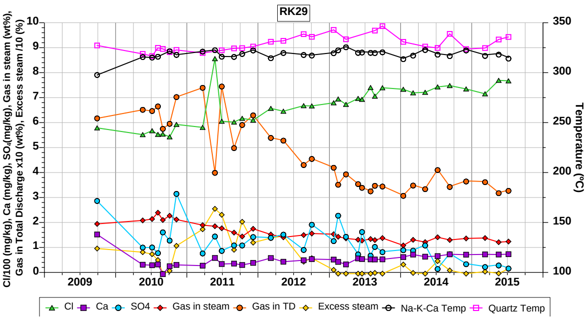

Figure 18: RK29. On the left axis is chemical constituents reservoir chloride, reservoir calcium and reservoir sulfate. Also on the left axis is gas in steam, gas in total discharge and excess steam. On the right axis is temperature from geothermometry with both Na-K-Ca and Quartz temperatures shown.

With confirmed injection returns to these wells it is interesting that sulfate has declined to these wells. The area around the injection wells is conceptualised to be near the upflow, having previously measured the highest temperatures in the field, this being prior to injection. This may indicate that through either re-heating, fluid mixing, fluid-rock interactions or a combination of processes, the sulfate is being lost out of the fluid.

With a continued increase in chloride it is possible to conduct a chloride mass balance. From the 2013 reservoir tracer test, the chloride concentration for each injectate is from one year prior. The formula used for calculating percentage injection in a given well is:

$$\%inj = \frac{[\mathrm{Cl}]2015 - [\mathrm{Cl}]2014}{[\mathrm{Cl}]\mathrm{injectate}2014 - [\mathrm{Cl}]2014}$$

Data used in the calculations is presented in Table 1 with outputs shown in Table 2 with a comparison to the 2013 reservoir tracer test results that are presented in Addison *et al.* (2015a).

Table 1: Chloride data used in Chloride Mass Balance calculations

	RK5	**RK14**	**RK29**	**RK33**
	ppm	*ppm*	*ppm*	*ppm*
[Cl] 2015 value for well	736	797	779	813
[Cl] 2014 value for well	693	767	730	800
[Cl] 2014 NAP Brine	1190	1190	1190	1190
[Cl] 2014 RK Injectate	600	600	600	600
[Cl] 2014 Weighted Average	971	971	971	971

Table 2: Calculated injection in production from chloride for each well for two scenarios compared to the 2013 Tracer Test results from RK24.

	RK5	**RK14**	**RK29**	**RK33**
Scenario 1 *Only NAP Brine*	8.7%	7.1%	10.7%	3.3%
Scenario 2 *Mass Weighted NAP Brine & RK Injectate*	15.5%	14.7%	20.3%	7.6%
2013 Tracer Test *RK24 Returns (portion of RK24 in well production)*	5.7%	8.0%	9.0%	1.4%

Based on results shown in Table 2 this indicates values relatively similar for the main tracer response wells of RK29, RK14 and RK5. RK14 sees a chloride response lower than its tracer test returns from only NAP Brine, indicating that it is likely supported by some RK Injectate as well, especially considering that the calculations for the 2013 reservoir tracer test have likely under-represented returns from RK24. Given the levels of pressure support seen in RK29, it is likely that in particular RK29 is obtaining support in addition to injection.

Boiling

RK17 and RK27 are part of the western pressure compartment which has demonstrated a >35 bar pressure drawdown since natural state (Hernandez *et al.*, 2015a). A chloride response for RK17 and RK27 is shown in Figure 19, which is shown alongside the measured downhole pressure for RK18L2. The geochemical response of these wells is consistent with a process dominated by significant boiling, likely due to the pressure drawdown.

The area exhibits a strongly increased chloride level and declining gas in total discharge. On these observations alone, it is difficult to distinguish between injection fluid chemical breakthrough and boiling, as both processes will generate a similar chemical response. However a lack of tracer returns from the 2013 reservoir tracer test indicates that boiling is the dominant process in these wells. By 2015 a strong gradient in chloride exists in the western edge of the production area, from RK17 through RK27-RK32-RK26-RK28.

Silica levels in the combined Nga Awa Purua production (Figure 8) shows a stabilisation at a similar time as chloride stabilisation in RK17 and RK27, in addition to pressure stabilisation (Figure 19). This may indicate that through boiling the silica concentrations were slightly elevated relative to the reservoir temperature quartz equilibration.

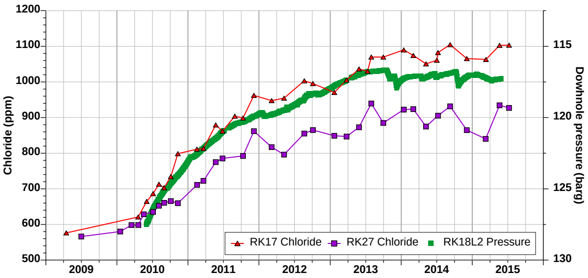

Figure 19: Chloride values for wells RK17 and RK27 (left axis) alongside downhole pressure measured in RK18L2 (right axis)

A plot showing the quartz enthalpy of the reservoir fluid and chloride for RK17 is shown in Figure 20, with different colours for each year the well has flown. Plotted alongside is the various injectate chemistries, with data from 2010 and 2015 shown for RK Injectate and NAP Brine. This indicates that boiling is occurring rather than data heading to one of the end-members.

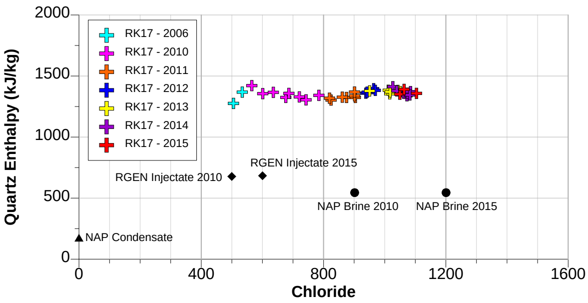

Figure 20: Enthalpy-Chloride plot showing fluid chemistry evolution for RK17 with different injectates chemistries shown.

Marginal Recharge

Wells RK13, RK26 and RK28 appear to be showing signs of dilution from an inferred cooler fluid source. These wells see declining chloride concentrations (Figure 21) and increasing sulfate (Figure 22) which are consistent with contributions from a marginal recharge. There is a possibility of a deep reservoir fluid being the source of this or a similar geochemical response would be expected from fluids formerly in the intermediate aquifer. Whilst these wells have lower geothermometry temperatures than the rest of the field, they have not seen much cooling in their fluid, perhaps seeing around 5˚C cooling since Nga Awa Purua start-up.

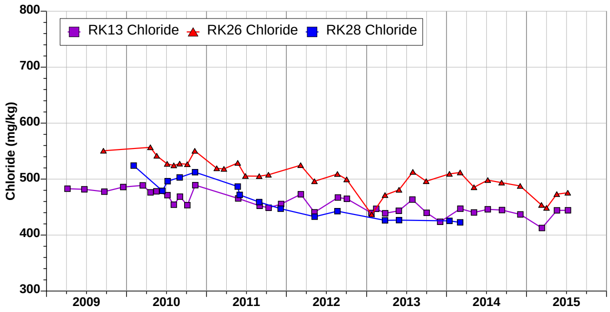

Figure 21: Chloride values for wells RK13, RK26 and RK28.

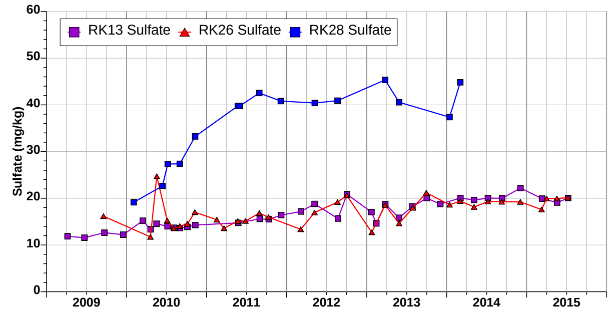

Figure 22: Sulfate values for wells RK13, RK26 and RK28.

CONCLUSION

Through a range of chemistry data sets, including: station chemistry, well chemistry, well flow, discharge enthalpy and reservoir tracer tests we have been able to identify the underlying reservoir processes at Rotokawa, especially when looked with other cross-disciplinary data sets such as downhole PTS runs, geophysics and geology etc. This cross-disciplinary approach has improved confidence in understanding of Rotokawa, enabling adaptive management to sustainable production from the reservoir.

ACKNOWLEDGEMENTS

The authors wish to sincerely thank the Rotokawa Joint Venture (Mighty River Power and Tauhara North No.2 Trust) for permission to publish this paper. Thank you to the operations team at the Rotokawa site for their support.

Thank you to everyone involved with sampling and analysis of all samples. This includes Papawera, Western Energy Services, MB Century and GNS Science, especially the NZ Geothermal Analytical Laboratory.

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