A Lookback on 20 Years of Production at the Rotokawa Geothermal Field

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ABSTRACT

The Rotokawa geothermal field celebrated its 20th anniversary of power production recently. The Rotokawa power station was first commissioned in 1997 at 24 MWe and was later expanded to 34 MWe. The Rotokawa geothermal field production was increased in 2010 to 172 MWe with the addition of the Nga Awa Purua power station. Currently, 12 wells serve as production wells and 6 serve as injection wells for the two power stations.

The development of the field has been a Maori landholder – industry partnership success story providing tangible benefits for both parties and for New Zealand as a whole. In this paper, we will: (1) Cover the high-level history of the field; (2) Discuss some of the insights gained through the development of the field, such as compartmentalisation; (3) Celebrate some recent successes – management of the reservoir pressure in the Western Compartment and the drilling one of the largest geothermal wells in the world.

1. INTRODUCTION

1.1 Geologic Setting

Volcanism in New Zealand is the result of plate tectonic interactions between the Australian and Pacific Plates. The Taupo Volcanic Zone (TVZ) is an actively rifting, intra-arc basin associated with the Hikurangi subduction system (McNamara, et al., 2016). The maximum rift extension rate seen is 13-19 mm/year offshore (Villamore and Berryman, 2006). The region is marked with significant geothermal activity and extends from Mount Ruapehu (central North Island) Northeast to the offshore White Island. The extent and layout of the TVZ can be seen in Figure 1 with known geothermal fields listed.

1.2 Historic Background

The Rotokawa ('bitter lake') geothermal system is located approximately 10 km north-east of Taupo. The area is marked by geothermal springs, fumaroles, and Sulphur deposits that were mined throughout the 1900's. Though there were no pre-European settlements at Lake Rotokawa, there were several adjacent Maori settlements and the area was used for bathing, cooking, and medicinal/therapeutic purposes.

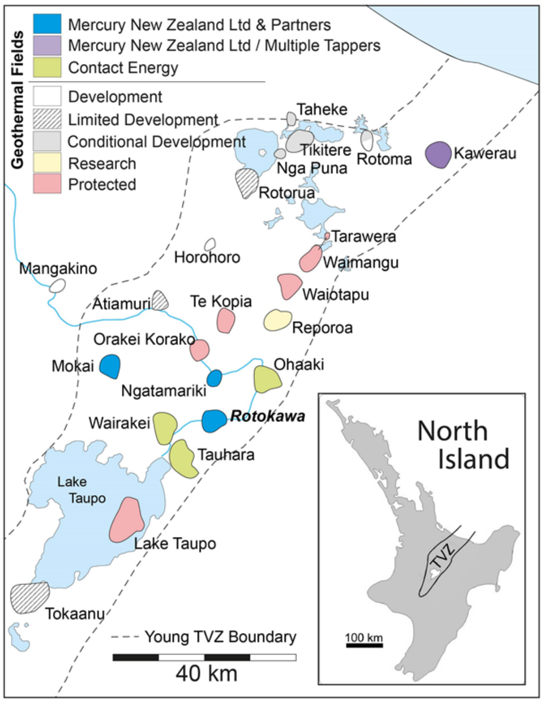

Figure 1: Location of known geothermal fields in the Taupo Volcanic Zone (TVZ) on the North Island of New Zealand (Bibby, et al., 1995). The Rotokawa field is approximately 10 km east of the Wairakei geothermal field.

The first exploration wells were drilled in the 1960s by the New Zealand government and indicated a hot convective system was present. RK01 had a maximum temperature of 307°C and was the hottest geothermal well in New Zealand at the time. In the mid-1980s, RK04 and RK05 were drilled to depths of 2500m and encountered temperatures of 330°C. Early testing indicated that RK05 had an estimated power capacity of 15 MWe.

In 1993, the Tauhara North No. 2 Trust (a Maori land owning trust), Taupo Electricity Ltd, and WORKS Geothermal Ltd were granted resource consents from the Waikato Regional Council to extract steam from the Rotokawa Geothermal Field for electricity generation (McNamara, et al. (2016); Bloomer (1995)). In 1997, under a joint venture of Tauhara North No.2 Trust and

Power New Zealand, electricity generation began with the installation of a Geothermal Combined Cycle technology utilizing a steam turbine and a binary plant for a combined 24 MWe (McNamara, et al. (2016)). The plant was extended to 34 MWe in 2003. In 2000, Mighty River Power Ltd acquired an interest in the field and combined with Tauhara North No.2 Trust to form the Rotokawa Joint Venture (RJV). The field was further extended in 2010 with the addition of a 138 MWe, triple-flash plant – Nga Awa Purua (NAP) power station. The total electrical generation capacity of the field is now 172 MWe. RK05 is still one of the 12 active production wells on the field.

Figure 2 shows the casing and total depths for all wells drilled at Rotokawa (top). In that figure, the first shallow exploratory Crown wells were drilled in the 1960s. That was followed by deeper exploration wells in the 1980s.

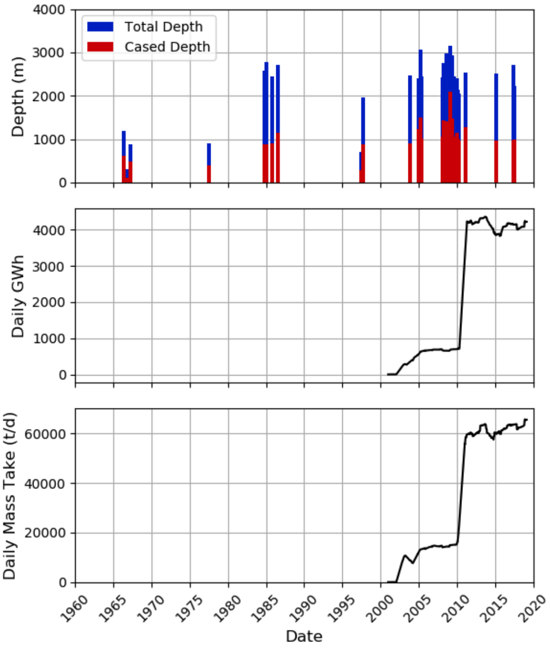

Figure 2: All Rotokawa well casing and total depths (top); rolling average daily GWh (middle); and rolling average daily mass take (bottom).

Three additional wells (RK9, RK11 and RK12) were drilled when electricity generation began in 1997. Five deep wells (RK13, RK14, RK16, RK17 and RK18) were drilled in 2002-2005 when the power station was expanded. An intensive drilling campaign (utilising two rigs) was undertaken from 2008-2010 in preparation for the 138 MW NAP power station. In the more recent years, the well frequency is settling into makeup well timing. The daily GWh and mass takes can be seen in the middle and bottom plots of Figure 2. The purpose of the plot is to highlight the time span from initial investigative drilling, to initial generation, to expansion, and to final generation capacity. In the following paper, we will expand on the details of the previous 20 years of field development at Rotokawa.

2. ROTOKAWA A (PRE-2010)

The initial 24 MWe power plant commissioned in 1997 was called Rotokawa A. The plant was extended to 34 MWe in 2003 with the addition of two combined cycle units. Following the plant expansion, the plant became known as RGEN. Before the addition of the second powerplant, Nga Awa Purua, an overarching theme at Rotokawa was chasing injection. This section will follow the initial development of the field and highlight the learnings of different injection strategies over that time period. Figure 4 shows the current layout of the wells on the field but includes historic/abandoned wells and will be used throughout this document for well references.

From 1997-2003, the two deep reservoir production wells servicing RGEN were RK05 and RK09. The station was consented for 15,500 t/d two-phase production. The production rate was typically around 10,800 t/d (450 t/h). Fluid was reinjected into the intermediate aquifer (~500-800 m) through RK11, RK12, and (to a lesser extent) RK01. The impact of the intermediate-depth injection was ground tumescence and an increase in surface feature activity. Further, reservoir tracer testing indicated that there was no connection between the intermediate aquifer and the deep reservoir. Figure 3 shows ground levelling trends at the field since 1997. The maximum tumescence was in the area of RK1, RK11, and RK12 and peaked at about 50 mm in 2004. Due to the tumescence observed, and an increase in surface feature activity, there was a desire to move injection from the intermediate aquifer and into the deep reservoir. However, that could not be achieved until new deep wells were drilled. The plot shows clearly that after injection was moved deep, there was a halt to further ground tumescence.

In 2003, a workover was undertaken on RK09 to replace the master valve and repair a corroded section of casing in the intermediate aquifer (400-800m). During the milling operation, the well bore was penetrated and maintaining a quench became difficult. The well was temporarily plugged and, in the end, never returned to service. With the expansion of the power station and the loss of RK09, RK13 was drilled in 2003 to help with generation requirements. In 2004, a drilling campaign began where 5 wells (RK14-18) were drilled and RK09 was plugged.

In the middle of the drilling campaign, after RK14 was drilled, it was soon brought into service as a production well. Within 60 days, RK13 was switched from production to injection and started receiving half of RK11's injectate. This enabled some injection to be moved out of the intermediate aquifer to help ease both the ground tumescence and increased surface feature activity. When RK16 was completed in the western area of the reservoir, most of the injection was directed into that well. RK13 was shut in to heat-up, and RK11 and RK12 were turned down to under 100 t/h each. The drilling campaign finished with the drilling of RK17 and RK18 in 2005, but neither well was used for 6 months.

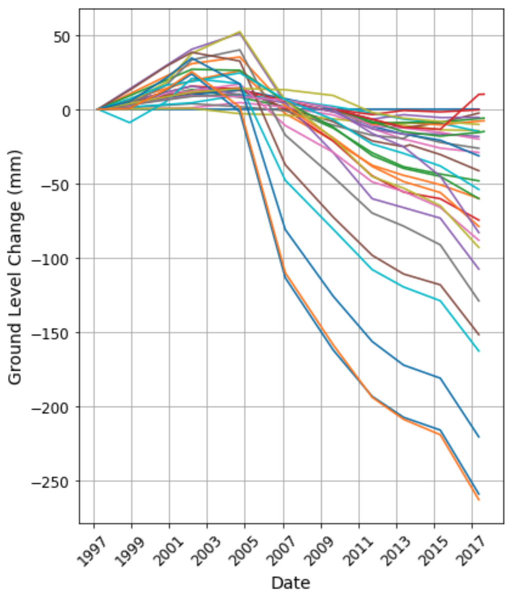

Figure 3: Ground level trends across RKA field since 1997. The area of maximum tumescence in 2005 was near the shallow injection area (RK11).

At the end of 2005, RK13 was flow tested and returned to production service. RK18 was tested for injection and used primarily instead of RK16. This enabled nearly all injection to be moved out of the intermediate aquifer. Figure 3 shows the impact that deep injection had on ground tumescence after 2005. During a brief period in 2006, RK17 was flow tested for production while RK16 and RK18 were being used for reinjection. Figure 5 shows the timing of well utilization from 2002-2009. The lines are colored red when the well was used for production and blue when used for injection.

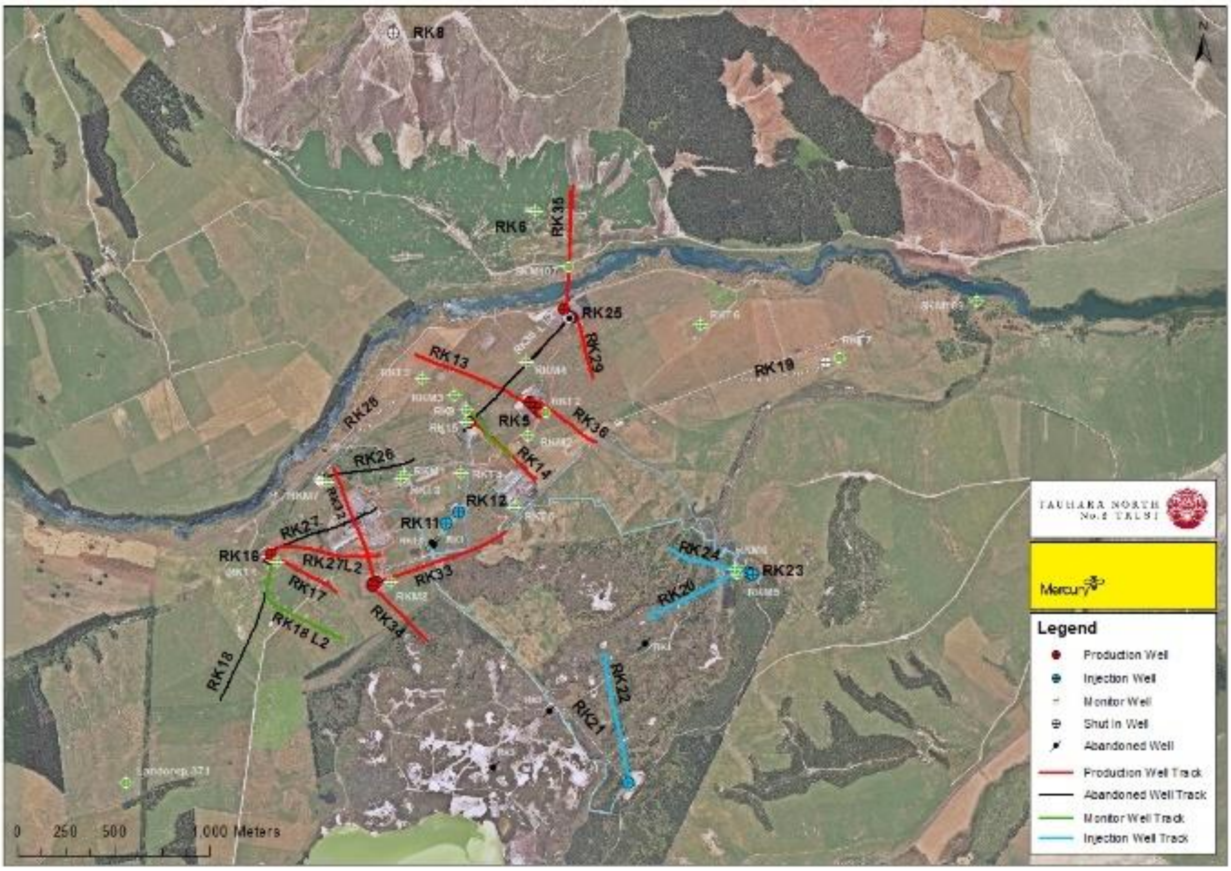

Figure 4: Current (2017) Rotokawa field well layout.

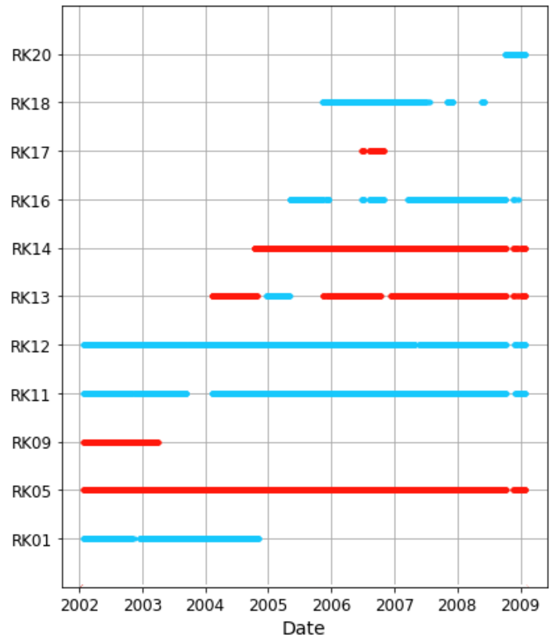

Figure 5: Well utilisation with injection (blue) and production (red).

In 2006, a reservoir tracer test was conducted to determine the connectivity between the injection wells RK16 and RK18 to the production wells (RK17, RK05, RK13, and RK14). Addison, et al. (2015a) provide a comprehensive summary of the tracer test history at Rotokawa. The tracer test in 2006 used isomers of naphthalene disulfonic acid (NSDA) into each RK16 and RK18. No tracer from RK16 was ever detected in any production well, indicating a poor connectivity to the rest of the reservoir. Returns from RK18 to RK17 were significant and rapid – reaching 21% returns only days after injection. Figure 6 and Figure 7 show the tracer return results in RK17 and RK13 respectively from 2006 (from Addison, et al. (2015a)).

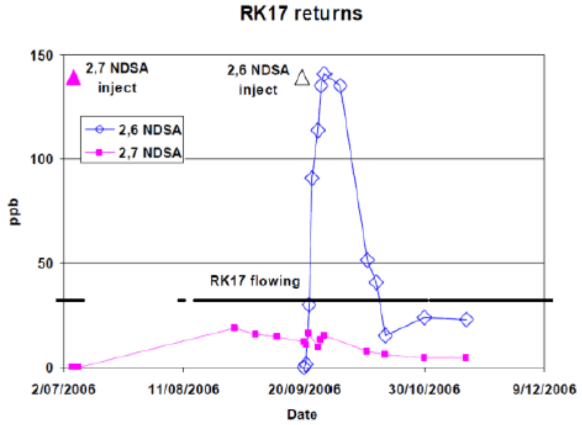

Figure 6: RK 17 tracer returns from RK18 (from Addison, et. al. (2015)).

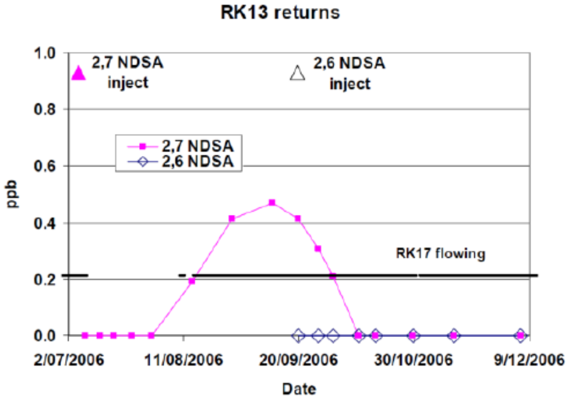

Figure 7: Tracer returns to RK13 from RK18 injection (from Addison, et. al. (2015a)).

The reservoir tracer test results indicated a fast connection between injection at RK18 and the rest of the field, most likely through a high permeability pathway of SW-NE orientation, which is consistent with the overall orientation of the TVZ. It was obvious that that injection strategy would not be feasible long term due to risks of production well cooling.

A desire to increase production on the field led to an assessment of well and power plant performance and behavior over 10 years of operation, in addition to updated conceptual and numerical models (Bowyer and Holt, 2010). These assessments indicated that the field could sustain a second power station. The planning of a second power station, Nga Awa Purua, was commenced and injection was planned to be moved off axis from the RK18-RK13 connection, toward the Southeast section of the field, where the current injection is located.

2.1 Geochemistry trends

Fluid extraction rates from RGEN production (about 15,000 t/d pre-NAP) were relatively small and prior to deep injection, this would have had minimal impact on the natural-state condition of the deep reservoir. Post-production geochemistry data for RGEN wells up to the start of deep injection (RK5, RK13, RK14), were demonstrably stable pre- and post-production.

Significant gradients in terms of Cl, Cl/B, Na-K-Ca geothermometry, and non-condensable gasses (NCGs) are observed across the field in the natural state, illustrated in Figure 8 (Winick, et al., 2011). The deep reservoir gradients appear to follow a SE-NW trend, perpendicular to the main structural axis of the production field and the TVZ. The data does not reveal any major vertical geochemical gradients on the basis of feed-zone distribution within the reservoir. Rather the dominant gradient in the main reservoir appears to be across the field, instead of with depth.

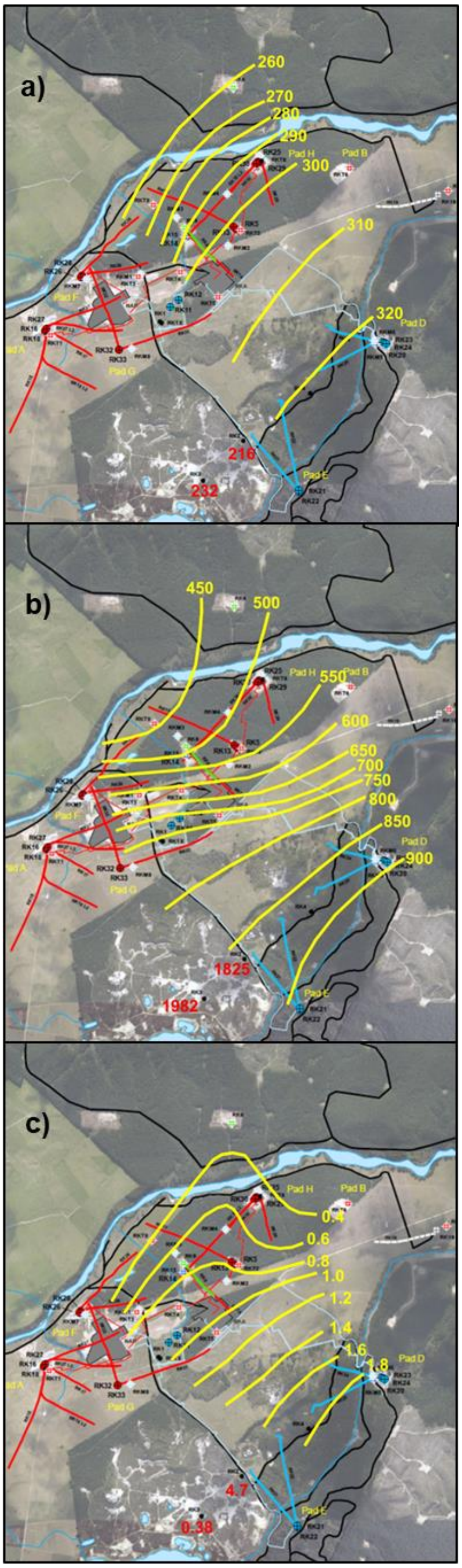

Figure 8: Isochemical contour maps for the Rotokawa field. a) NKC geothermometer temperature (°C), b) Reservoir chloride (mg/kg), and c) Wt% NCG in total discharge from the reservoir (Winick, et al., 2011).

3. NGA AWA PURUA (SINCE 2010)

3.1 History

The Nga Awa Purua expansion began in 2008 with a drilling campaign that drilled wells RK19-RK33 and the construction of the Nga Awa Purua power station that would utilize a triple-flash steam single-shaft steam turbine, the largest single-shaft geothermal unit in the world. The plant features a direct-contact condenser and makes use of brine acid-dosing with sulfuric acid. The consented two-phase take was ultimately increased to 65,500 t/d.

When RK20 was drilled in 2008, nearly 100% of the Rotokawa injection was moved to that deep well. RK22 reached a maximum downhole temperature of 337°C, making it the hottest well in New Zealand. Figure 9 shows the current steamfield diagram for the field. Wells RK32, RK33, and RK34 can flow to either station. Currently RK32 flows to RGEN and RK33 and RK34 flow to NAP. The production/injection history since NAP has come online has led to large number of new understandings about the Rotokawa geothermal system. The overarching themes are reservoir compartmentalization (no field-wide steam cap evolution), marginal recharge, and injection returns from additional reservoir tracer tests.

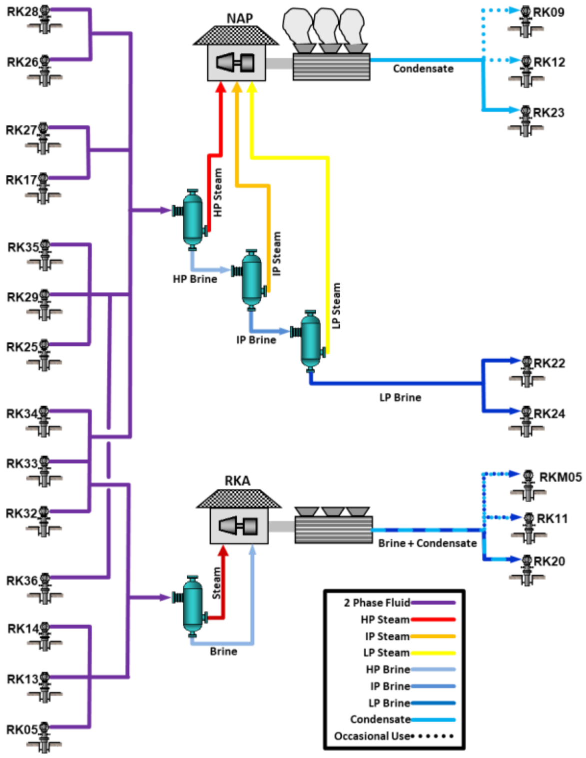

Figure 9: Rotokawa steamfield flow diagram as of late 2017.

3.2 Compartmentalisation

Quinao, et. al. (2013) and Hernandez, et al. (2015) provide an overview of the reservoir compartmentalisation present in Rotokawa. There are large differences in pressure drawdown in different parts of the reservoir, sometimes over very small production areas. This suggests heterogenous permeability and/or strong pressure controls across the field. Figure 10 shows the pressure drawdown in the deep reservoir from 2015. The wells in the western part of the field (RK18, RK17, RK27, RK28, RK26, RK13) show a similar pressure response consistent with a finite compartment. This group of wells has been termed the “western compartment”.

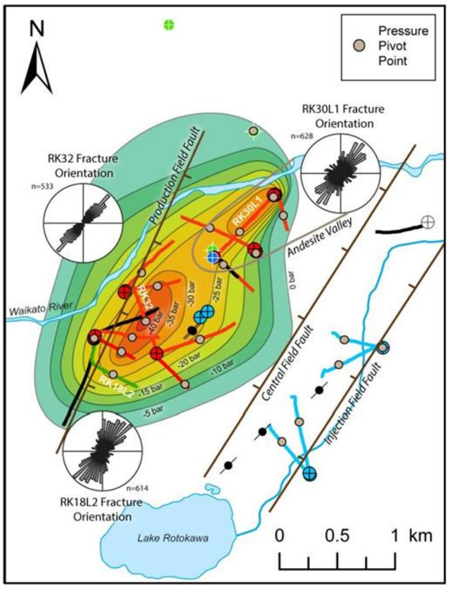

Figure 10: Pressure drawdown in deep reservoir (Hernandez et al., 2015).

RK18 was side-tracked (RK18L2) and the well is used for pressure monitoring of the western compartment. Western compartment pressure drop from natural state peaked at nearly 40 bar in RK32. There was also a localized pressure drop of about 30 bar near RK25 in the northeast part of the production field. The behavior of RK25 indicates that the well is in a very small compartment with poor permeability. However, wells in the center of the reservoir, e.g., RK05, RK29, and RK36 tend to have more conservative pressure decline – 10 bar, 4 bar, and 4 bar respectively. This is likely due to injection returns and the possibility of high natural upflow of hot fluid in the area. Injecting in the hottest part of the field (RK22) provides a good opportunity for injectate to heatup on its return to the production area.

3.3 Geochemistry trends

The response to increased production of the Rotokawa field with the startup of NAP can be largely classified into three groupings based on geochemical trends, as is shown in Figure 11.

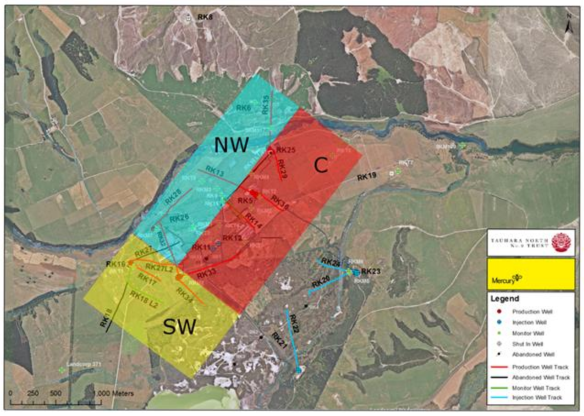

Figure 11: Geochemical grouping of Rotokawa production wells.

The central wells are the heart of the field, estimated to be capable of producing up to 117 MWe combined, the main geochemical process in these central wells is injection returns. The north-west wells are impacted by marginal recharge and the south west wells are undergoing boiling. These processes are discussed in the following sections of this paper.

3.3.1 Injection returns

The central wells comprise RK05, RK14, RK25, RK29, RK30, RK33, and RK36. These wells have seen a gradual increase in chloride since NAP began production in 2010, Figure 12. The injection chloride of NAP brine has gradually increased overtime because of the triple-flash plant and injection return loop.

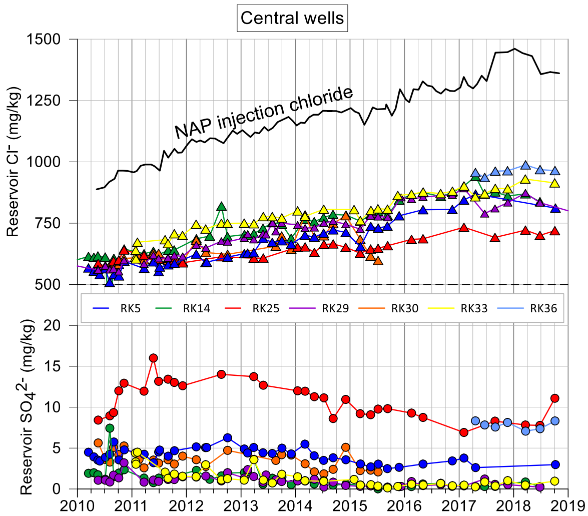

Figure 12: Reservoir chloride and sulfate trends for the central wells at Rotokawa.

Injection returns at Rotokawa have been characterized by multiple reservoir tracer tests, see Addison et al. (2015a) for an overview. Specifically, the return of NAP brine to these wells has been confirmed by two iodine-125 tracer tests in 2013 and 2015. No significant cooling is observed in these wells, the deep injection has sufficient time to heat up on the return to the production area, likely as a result of the faults which run in a south-west to north-east orientation.

The brine injectate from NAP has an elevated sulfate concentration when it is injected due to sulfuric acid dosing at the NAP power station to inhibit silica scaling. Interestingly there is a low concentration of sulfate in the wells that are connected to injection, most likely due to deposition of anhydrite on the fluids return path to the production area.

RK36 commenced flow in the first half of 2017, and this well has the highest reservoir chloride in this part of the reservoir, having what is expected to be a higher degree of injection returns supplying this well. The commencement of flow from RK36 has influenced the other wells in this area, with an associated reduction in chloride seen in RK14 and RK29.

3.3.2 Marginal recharge

The north-west wells have generally seen a lower concentration of chloride, a higher concentration of sulfate and lower geothermometer temperatures.

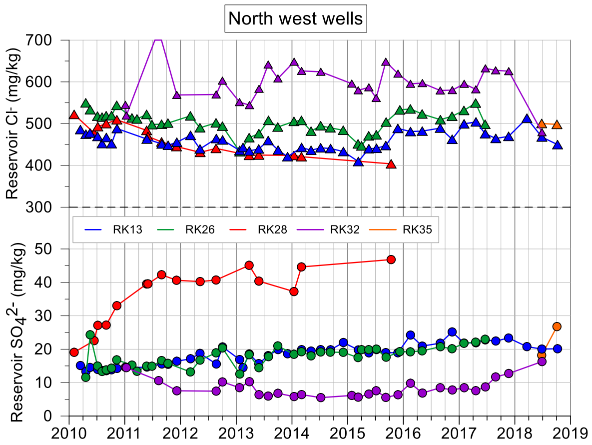

Figure 13: Reservoir chloride and sulfate trends for the north-west wells at Rotokawa.

The fluid chemistry of the wells is influenced by marginal recharge coming from the northwestern area of the field. Mixing with cooler dilute fluid leads to a slight long-term dilution trend for these wells, as indicated by the continuous decrease in chloride concentration since 2010 (Figure 13). Calcium and sulfate concentrations have also increased over time, likely due to the retrograde solubility of anhydrite, with higher concentrations of calcium and sulfate in the cooler marginal fluid. This could be due to a lateral recharge or potentially some form of downflow. Gas in total flow and gas in steam are stable for RK13, while a declining trend is observed for RK26 as a result of mixing with degassed fluid. The geothermometers are stable for RK26, indicating sufficient heating of the marginal recharge fluids prior to mixing with the production fluid. A minor declining trend is observed for the RK13 geothermometers, indicating that the marginal recharge was not fully heated prior to reaching RK13.

In 2015, a recovery in chloride concentration was observed in both RK13 and RK26, and since then appeared to have stabilised up to the end of this reporting period. This is attributed to reduced take at RK13, RK26 and RK28, and consistent with the pressure stabilisation observed in the western compartment based from RK18L2 pressure monitoring. This has subsequently reduced the entry of marginal recharge into the western compartment, hence the stabilisation of the chloride trends in these wells.

3.3.3 Boiling

Upon commencing production RK17 and RK27(L2) saw dramatic increases in reservoir chloride concentrations, as shown in Figure 14. This is attributed to boiling on the western edge of the field in response to the pressure draw down in this area, over time the chloride level has stabilised as would be expected. RK34 has seen a reduction in excess steam since the well commenced flow in 2015.

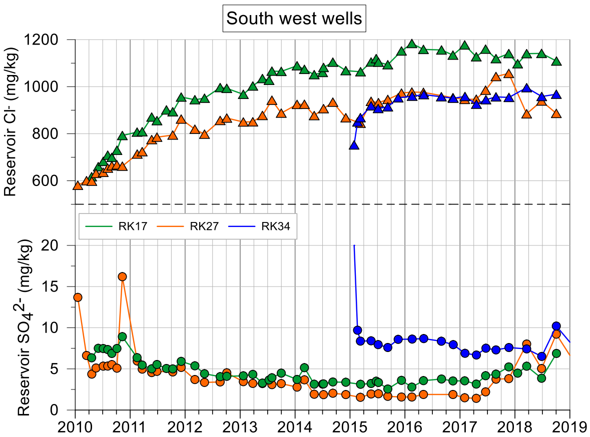

Figure 14: Reservoir chloride and sulphate trends for the south west wells at Rotokawa.

The boiling in this area of the reservoir has been monitored closely by RK18(L2) pressure and steps have been taken to spread production and reduce the drawdown in the western compartment, as discussed below.

4. RECENT SUCCESSES

4.1 Western Compartment Pressure

As mentioned above, a study by Quinao, et al. (2013) identified the pressure drawdown in the western part of the field as being consistent with a finite reservoir compartment. That area of the field is termed the Western Compartment. Wells RK18(L2), RK17, RK27, RK32, RK26, and RK28 are considered part of the Western Compartment. The pressure drop in that area of the field has been significant and consistent with production from that area. Figure 15 shows the Western Compartment total mass take (top) and the downhole pressure in several wells (bottom) over time since 2010. In the pressure plot (bottom), the blue line is the continuously monitored downhole pressure in RK18(L2). The dashed lines are from shut pressure/temperature/spinner (PTS) surveys in other wells. Nearly all the Western Compartment wells have high flowrates, so it was a preferred area of production for a long time. The flowrate averaged about 1300-1400 t/h for a 7-year period from 2010-2017. The pressure drop did seem to stabilise, however wells RK28 and RK26 were experiencing cooling due to marginal recharge as well. RK32 experienced the largest pressure drawdown in the area (about 40 bar) in 2013. The high pressure drop and risk of increasing the entry rate of marginal recharge led to a desire to spread production in the field. That was one purpose of the drilling campaign in 2017.

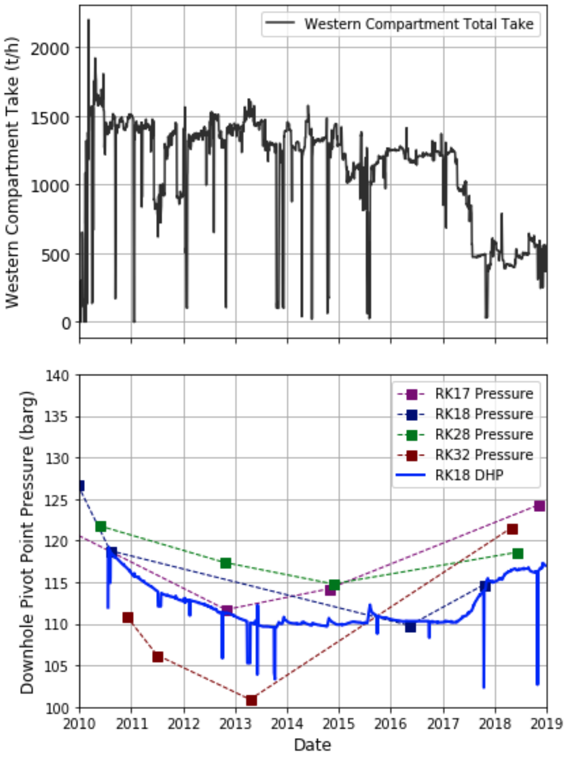

Figure 15: Western Compartment total mass take (top) and pressure response in wells since 2010.

The mass take plot of Figure 15 shows that take was significantly reduced, following new well drilling in 2017, and the pressure has correspondingly increased in the Western Compartment. RK18(L2) has experienced over 6 bar of pressure recovery and a shut PTS in RK32 has shown over 20 bar of recovery since peak drawdown levels. This pressure recovery helps to reduce the risk of additional marginal recharge in the area and slow the pressure-related decline of wells in the area.

4.2 2017 Drilling Campaign

A drilling campaign was commenced in 2017. The purpose was to drill two new production wells in order to spread production in the field, helping reduce the power density and to reduce the take from the Western Compartment. The campaign was also an opportunity to implement new well designs with big bore (13 3/8”) casing to allow for the potential installation of corrosion resistant alloy liners. Further, works were planned to install an alloy sleeve in RK29 due to the occurrence of external casing corrosion.

External casing corrosion in the aquifers above the deep reservoir is a challenge at Rotokawa, with corrosion observed generally over a range of 100-1000 mD (meters depth) as seen in Figure 16. Traditionally, corrosive damage is seen in about 50% of wells at Rotokawa. Of those, some wells are small, and the installation of alloy liners is cost-prohibitive. This drilling campaign was unique, because the potential of alloy liners was ‘pre-built’ into the well design with large diameter (13 3/8”) casing. If the wells do experience corrosion, they would receive a 9 5/8” liner instead of the 7” liner as inserted into RK29. This would have a positive impact on the final flow capacity of the well.

External corrosion at Rotokawa is dominated by carbonic acid, however there are occurrences of alteration that indicate the presence of sulfuric acid. RK29 had an area of complete casing metal loss around 750 mD caused by external carbonic acid corrosion. At the time, RK29 was the largest well in the field, accounting for nearly 40 MWe at NAP and a capacity flowrate of nearly 700 t/h. A 7” alloy sleeve was used to successfully repair RK29. The well capacity subsequently reduced 15% as a result of the constriction of the smaller diameter wellbore in the sleeved section.

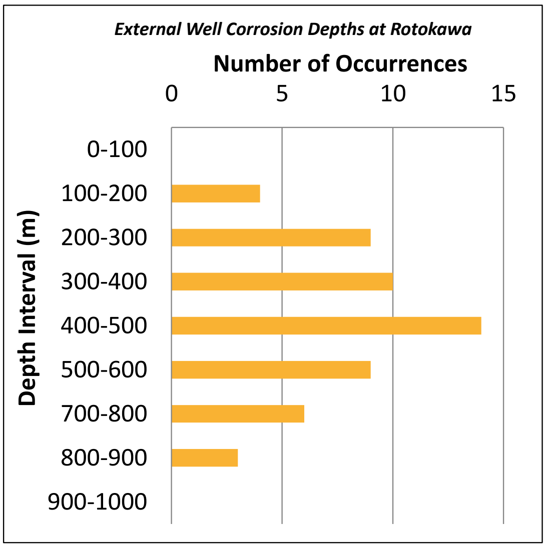

Figure 16: Individual occurrences of external metal loss zones with depth (from surface) at Rotokawa identified through HTCC logs. N.B. these are discrete occurrences where a well can have more than one occurrence in the depth interval, therefore not the number of wells with corrosion at that depth interval (from Addison et al, 2015b)

The wells planned to be drilled were RK35 and RK36. RK35 was the first Rotokawa production well to be deviated north of the Waikato River. The wellhead is located on H pad with RK29 and RK25, which is south of the river. RK36 was drilled near RK29 in an area of the reservoir expected to have high permeability and thought to receive injection pressure support.

RK35 turned out to be a reasonable flowing well (~300-350 t/h capacity), however enthalpy is in the lower range of the wells feeding NAP, at 1420 kJ/kg, whilst NAP runs at an optimum level at >1500 kJ/kg (Hoepfinger, et al., 2015). The benefit of RK35 is a knowledge of reservoir conditions in a previously unused part of the reservoir (North of the Waikato River) and the additional ability to spread production.

RK36 has a well capacity >900 t/h, with an enthalpy (from TFT) of just under 1500 kJ/kg. This translates into 50+ MWe at NAP. Having such a large well has enabled the mass take in the Western Compartment to be reduced dramatically as seen in Figure 15. One impact of RK36 was highlighted in the previous section – injection returns. It does seem that chloride trends are levelling off in nearby wells, indicating that they are receiving less injection support than in the past. Due to the large capacity of the well and therefore spare production capacity in the field it has enabled different field production strategies, such as fluctuating production from other areas of the field, e.g., RK35, Western Compartment, and RK29.

Productivity in geothermal wells is dependent on permeability, pressure and temperature. Rotokawa has very heterogenous permeability as discussed in the compartmentalisation section. To date, there have been 16 production wells on the Rotokawa field. There is a high degree of variability in well pressure decline due to the heterogenous permeability. This results in a long-tailed distribution of well capacities.

Figure 17 shows the distribution of well capacities in flow rates (top) and estimated MWe (bottom).

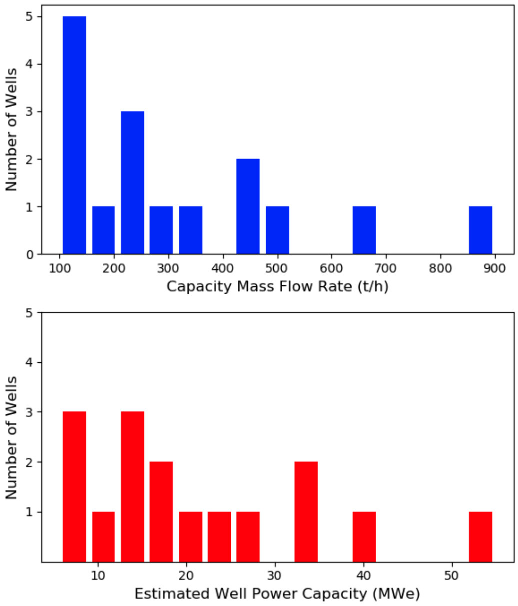

Figure 17: Production well flow capacities (top) and estimated power capacities (bottom) at Rotokawa.

5. LOOK AHEAD/CONCLUSION

As highlighted here, through development on the field there has been significant learning about the field. The immediate future holds some exciting opportunities. The first is finding the right balance of production spread with the new addition of RK35 and RK36. The drilling campaign of 2017 enabled production to be moved away from the Western Compartment. However, now a handful of wells in the centre of the field account for about 65% of the field's generation capacity. A key objective moving forward is to determine an optimal and sustainable spread of production in the field. RK35 will play a critical part in that spread. Also, we are actively trialling different strategies in the Western Compartment to determine a sustainable level of production in that area. Further, the potential of new wells in the North, Northwest, and South parts of the field could also provide opportunities to optimise field layout further.

An additional opportunity moving forward is the challenge of surface to resource alignment. This is not a unique challenge to Rotokawa, but the goal is to make the surface infrastructure optimised for the resource's flow and enthalpy capacities. There are two powerplants on the Rotokawa field. Currently most production wells are only set to flow to one station and based on well enthalpies, the station it flows to may not be optimal. NAP, with its triple-flash steam turbine requires a high level of steam. For example: RK35, with 1420 kJ/kg enthalpy, flows to NAP. However, RGEN could more efficiently handle the relatively higher brine fraction with its binary units. We are currently working through an enthalpy rebalance project to determine how to more optimally use the field's resources.

A great deal has been learnt about the Rotokawa geothermal system over the past 20 years. As a result, we now have a better understanding: the pressure connection between the intermediate aquifer and surface features through the effects of shallow injection; the connection of the Western Compartment wells through early reservoir tracer tests and later pressure correlations; the relatively heterogenous permeability structure; the chloride dilution trends and areas at higher risk of marginal recharge; as well as planning strategies for coping with acid corrosion in wells. The field has also had some recent successes, such as the recovery of pressure in the Western Compartment and drilling one of the largest geothermal wells in the world.

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