CASE STUDY OF MASS FLOW DECLINE IN PRODUCTION WELL NM11

George Allan[1], Alan Ferguson[2], Aimee Calibugan[1], and Jamie Potter[1]

[1] Mercury Ltd, 283 Vaughan Rd, Rotorua 3010, New Zealand

[2] Contact Energy Ltd, Private Bag 2001, Taupo 3352, New Zealand

Jamie.Potter@Mercury.co.nz

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ABSTRACT

NM11 is an inactive production well at Ngatamariki geothermal field drilled 3km deep. It is a large diameter well with an 18-5/8" production casing. The well was first flowed in 2013, initially providing approximately 1000t/h. A few months after starting production, the mass flow from the well began to decline. Calcite scale was detected in the well 10 months after beginning production. Managing calcite scale in production wells and power plants is a major challenge in geothermal field operations. The well was ultimately rendered unproductive and understanding the mechanism will lead to appropriate management options for future wells.

Geological, reservoir engineering, and geochemical data are investigated to determine possible causes for the decline observed in the well's productivity. The geology of the well and characteristics of two cores are inspected and compared to neighboring wells. PTS results before production and after 6 months of production show significant permeability reduction in all feedzones over the first 6 months of production. Wellbore models are used to match the PTS results and give modelled productivity index (PI), pressure, and enthalpy for each of the 9 feedzones. Geochemical data showed the well had calcite scale deposition occurring. Calcite scaling is induced by flashing, typically at inferred flash point depth. Scaling is a likely cause of productivity decline in shallow feedzones but does not explain the productivity index in lower feedzones which have not experienced flashing. Thermal expansion and collapse of weak formation are possible contributors to the observed permeability decline.

1 INTRODUCTION

NM11 was a production well at Ngatamariki geothermal field drilled to approximately 3km depth. It is a large diameter well with an 18-5/8" production casing. The well was first flowed in 2013. A few months after starting production, the mass flow declined (Figure 1). All available data has been assessed to find a possible cause, or causes, for the decline seen in the well. A brief history of the well is as follows:

1. Rapid production decline after start-up in 2013
    - "Skin" damage and wellbore blockage due to calcite scaling found after 10 months
2. Monthly mechanical broaching to clear the wellbore
3. Workover & first acid job (May 2015) – blockage cleared
4. Well throttled and antiscalant installed – no wellbore blockage
5. Second acid job (Nov 2016) – to address "skin" damage
    - Blockage observed at 1846m and confirmed as formation fill related to liner collapse

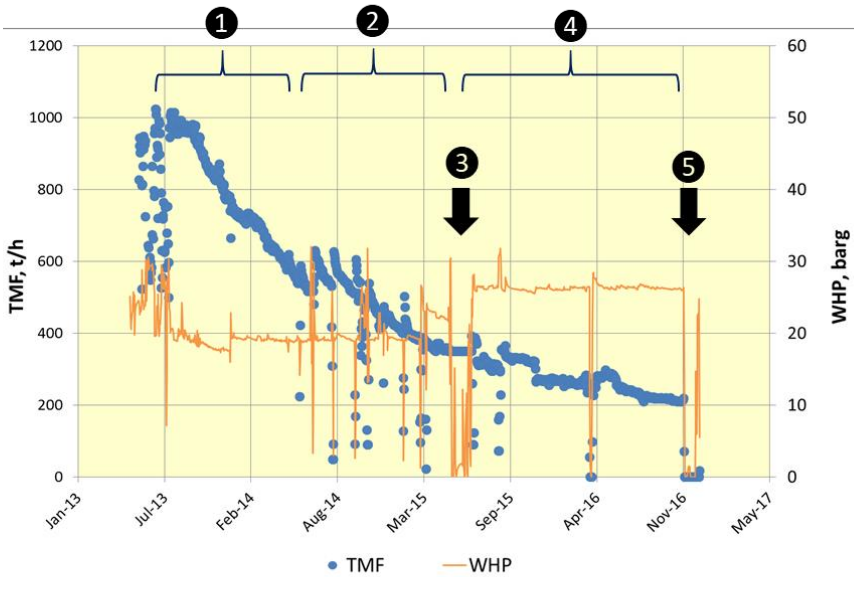

Figure 1. NM11 mass flow and wellhead pressure over time.

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2 NM11 GEOLOGY

A comparison of NM11 geology versus the offset well NM05 is shown in Figure 2. The identified permeable zones of these wells are primarily within the Tahorakuri Formation and Rotokawa Andesite. There were two cores recovered at NM11 and Table 1 summarizes the permeability characteristics of the cores. The presence of abundant fractures in NM11 core 2 as well as the total circulation losses incurred while drilling within the Rotokawa Andesite are indications of good permeability within this formation. On the other hand, the observed partial drilling circulation losses of up to 700 bbls/hr, the presence of natural fractures, and the interconnected matrix porosity account for the permeability within the Tahorakuri Formation. For comparison, a core from the Tahorakuri Formation at the nearby NM13 showed a lack of veins except for a 2.7 cm wide vein with common branching ('sheeted-like') to micro-brecciated fractures filled by clinozoisite with minor epidote. As shown in Figure 2, zones of washouts (due to unstable formation) have been identified below the production casing shoe of NM11 (and NM05). These zones coincide with intensely altered pyroclastics (Tahorakuri Formation). The blockage tagged at 1846m (indicated as maximum cleared depth in Figure 2), after the second acid job, is within the washout zones. There are faults identified around NM11 area and it is inferred that one of these faults is potentially acting as conduit of cooler fluid to downflow into the reservoir. This is further discussed in the geochemistry section.

Table 1. Permeability characteristics of the NM11 cores.

NM11 Cores	Structural Features – Fractures and Veins	Circulation Losses (bbls/hr)
Core 1: 2083 – 2089.1 mRF strongly altered tuff (Tahorakuri Formation - 1110 to >2315 mRF)	• Veins are rare and most of the veins appear sealed (epidote + calcite + clay ± wairakite + chlorite + hematite) • Two natural fractures (i.e. not coring-induced) containing secondary minerals. No evidence of movement (e.g. slickenlines, fracture steps) are present. • Interconnected matrix porosity may account for at least some of the permeability at these depths	Intermittent circulation losses up to 700 bbls/hr from 2083 -2315 mRF
Core 2: 2999 – 3001.5 mRF strongly altered porphyritic andesite (Rotokawa Andesite - <2999 to >3001 mRF)	• Veins are abundant and mostly narrow (~1mm) except at vein intersections (~10 mm); there are indications of open-space deposition (e.g. euhedral wairakite) • Fractures are abundant in the core • Some fractures contain slickenlines indicating movement • Abundant fractures indicate fracture-controlled permeability	Total circulation losses from 2315 mRF

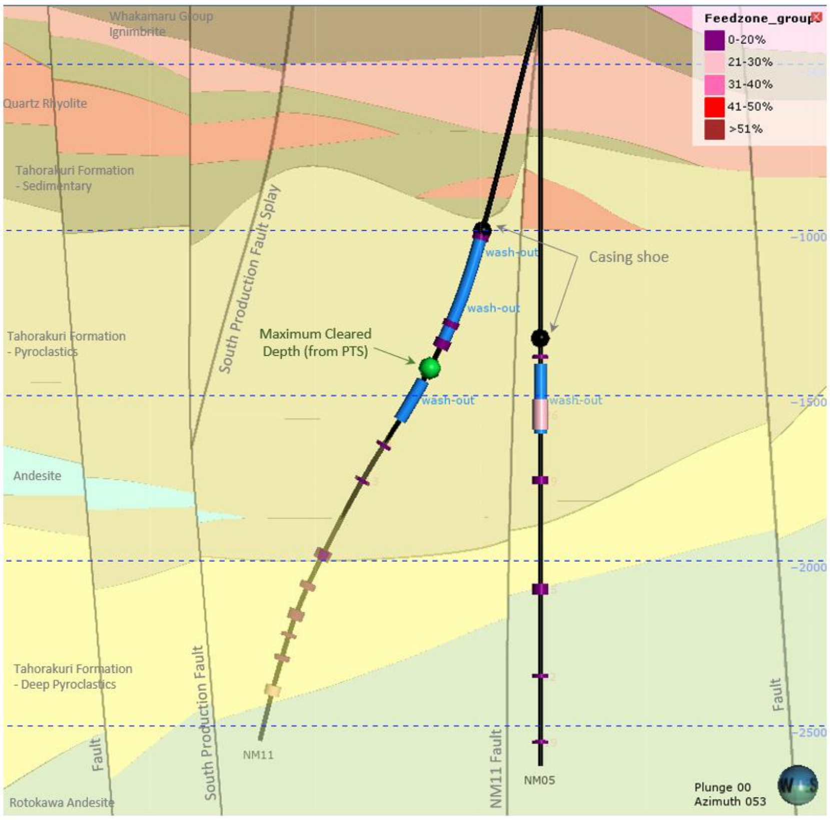

Figure 2. A cross-section showing NM11 geology versus offset well NM05.

3 NM11 RESERVOIR ENGINEERING DATA

Flowing pressure, temperature, and spinner surveys (PTS) were run in NM11 during the first few months of production. To investigate the observed mass flow decline, a PTS before sustained production (June 2013) is compared to a PTS after 6 months of production (December 2013) – both circled in Figure 3. The June and December 2013 PTS surveys are shown below in Figure 5.

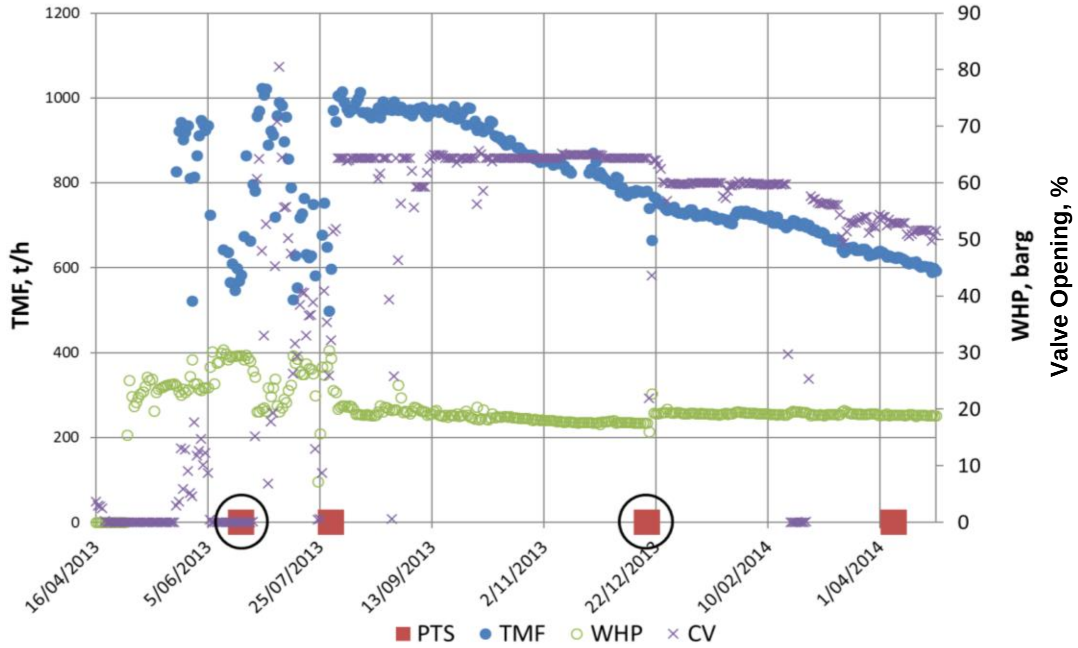

Figure 3. NM11 Mass Flow (TMF), Wellhead Pressure (WHP), Control Valve Opening (CV), and PTS dates

The first PTS occurred in June 2013, before the well was extensively used for power generation. The average wellhead pressure on the day was 30.6 barg and average mass flow was 650 t/h. The well is modelled with 9 feedzones, with the shallowest located at -1465m. The PI of the feedzones are in Table 2. The total PI for the well was 37 t/h/bar, however this is distributed across the 9 smaller feedzones, many of which are spread over tens of meters. For comparison, NM07, NM12, and NM13 all produce mainly from 1-2 exceptionally large feedzones with PI of above 20 t/h/bar.

Table 2. Feedzones in June 2013 PTS compared to December 2013 PTS

Feedzone Elevation (m)	June 2013			December 2013		
	Pressure (bara)	**Enthalpy (kJ/kg)**	**PI (t/h/bar)**	**Pressure (bara)**	**Enthalpy (kJ/kg)**	**PI (t/h/bar)**
-1465m	148.2	1210	1.97	138.2	1242	0.79
-1559m	155.3	1210	3.74	145.3	1242	1.49
-1662m	163.0	1215	2.24	153.0	1242	0.90
-1763m	170.5	1220	3.94	160.5	1243	0.79
-1970m	186.1	1220	3.94	176.1	1245	0.79
-2064m	193.1	1220	6.31	183.1	1241	2.53
-2204m	203.5	1225	4.65	193.5	1236	2.79
-2345m	214.1	1205	8.08	204.1	1232	4.85
-2426m	220.1	1172	1.83	210.1	1229	0.37
			36.72			**15.29**

Figure 4 below shows a comparison between the PTS velocities in NM07, NM11, and NM13, all at similar flowrates, to illustrate the difference in feedzone characteristics. The sharp inflows at 1500m and 2100m in NM07 and NM13 respectively are markedly different to the gradual inflow from 2500 – 3000m in NM11. NM11 feedzones in the upper section are masked by the wellbore wash-out.

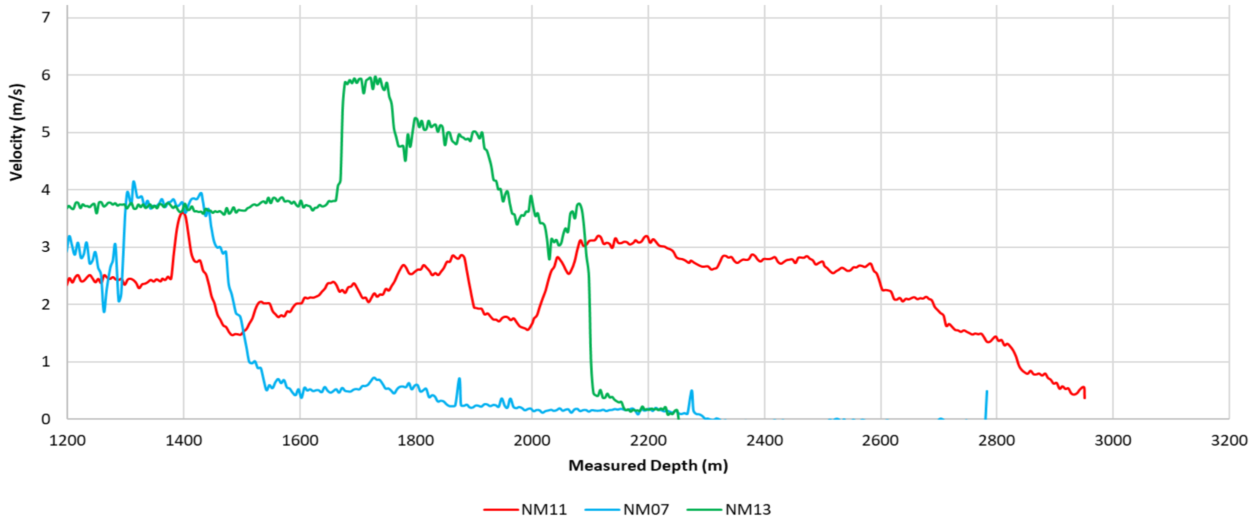

Figure 4: PTS velocities in NM07, NM11, and NM13

The flow from NM11 appeared stable initially but can be seen to decline around October 2013. The second PTS occurred in December 2013 after 6 months of production. The daily average wellhead pressure was 18 barg and average mass flow was 660 t/h. The pressure in the well, and therefore flash depth, is significantly lower (Figure 5). All feedzones of the well have heated, particularly the deeper feedzones. The temperature rose 5°C for feedzones above -2100m and rose 10°C in the bottom two feedzones. The flowing pressure in NM11 is 50 bar lower than the June PTS. Pressure drawdown in the reservoir is measured as less than 3 bar in monitoring wells and less than 10 bar in nearby production wells. Assuming the reservoir pressure decreased by 10 bar surrounding the well, the PI of all feedzones reduced by roughly 60% after the first 6 months of operation (Table 2). The total PI for the well is 13 t/h/bar.

After 2013, the decline of the well appears to be predominantly due to wellbore scaling – increases in wellbore rugosity and decreases in diameter match the PTS surveys and the well performance better than further PI reduction. In Figure 5, the results of a PTS survey in December 2014 show significant velocity increases and pressure drops when compared to June 2013, highlighting wellbore scaling between 1400 – 1800m, particularly around 1700m. Broaching confirmed scale at these depths. The evolution of modelled PI over the life of the well is shown as a stacked plot in Figure 6. This is compared to the overall enthalpy of the well from PTS surveys.

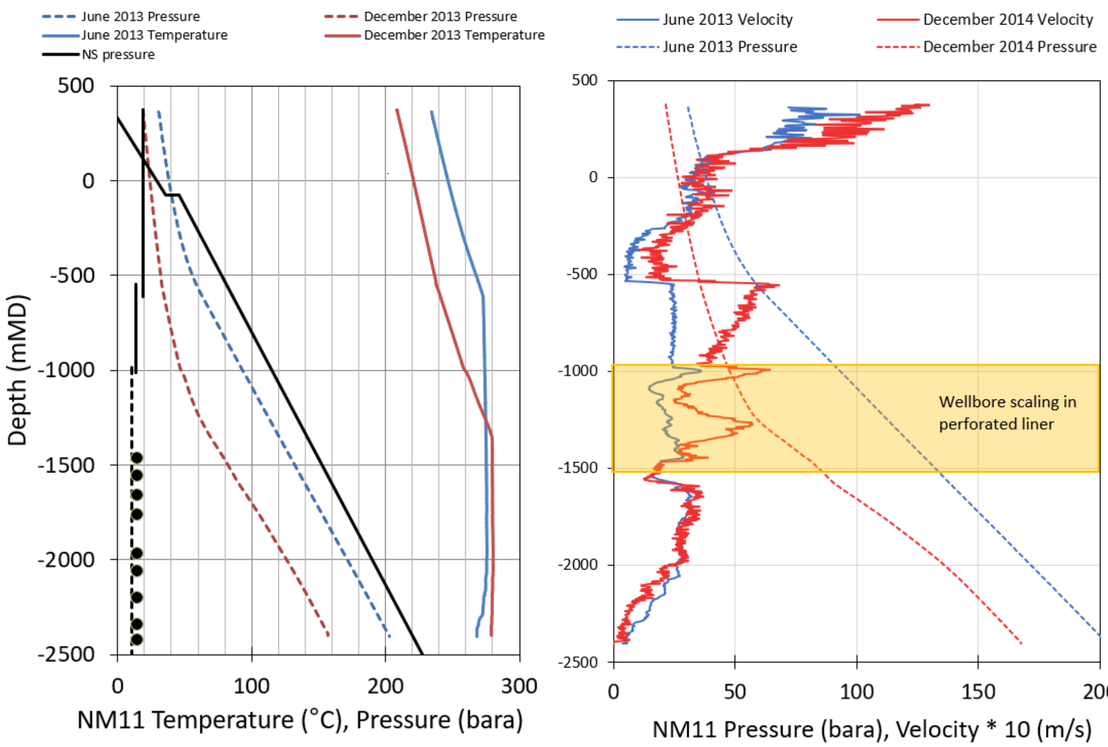

Figure 5: Left: NM11 PTS surveys in June and December 2013, at similar flowrates. Natural state (pre-production) pressure is shown in black. Right: NM11 PTS surveys in June 2013 and December 2014, highlighting wellbore scale buildup in perforated liner.

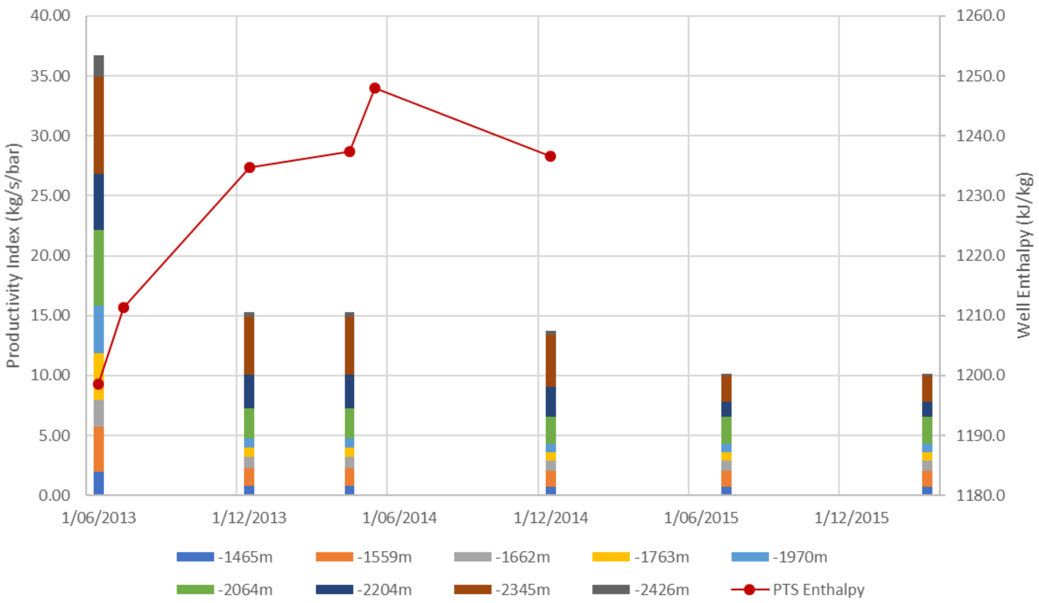

Figure 6: Evolution of individual feedzone PI in NM11 from modelled PTS surveys compared to overall well enthalpy.

4 NM11 GEOCHEMISTRY DATA

In natural state, and during production, the chloride concentration in NM11 indicated a more dilute fluid than other production wells (Figure 7). This is interpreted as a possible indication of marginal fluids entering into this area of the reservoir. Chloride trends since 2016 suggest that dilution is now becoming more widespread, likely triggered by production from the center of the field. The calcium concentration in NM11 was also lower than the other production wells, which may be correlated to calcite deposition in the formation and/or wellbore. Once antiscalant dosing started in 2015 the calcium concentration in NM11 recovered to a similar level to NM5 and NM12. Gas concentrations were similar in all production wells, with degassing apparent over the first few years of production.

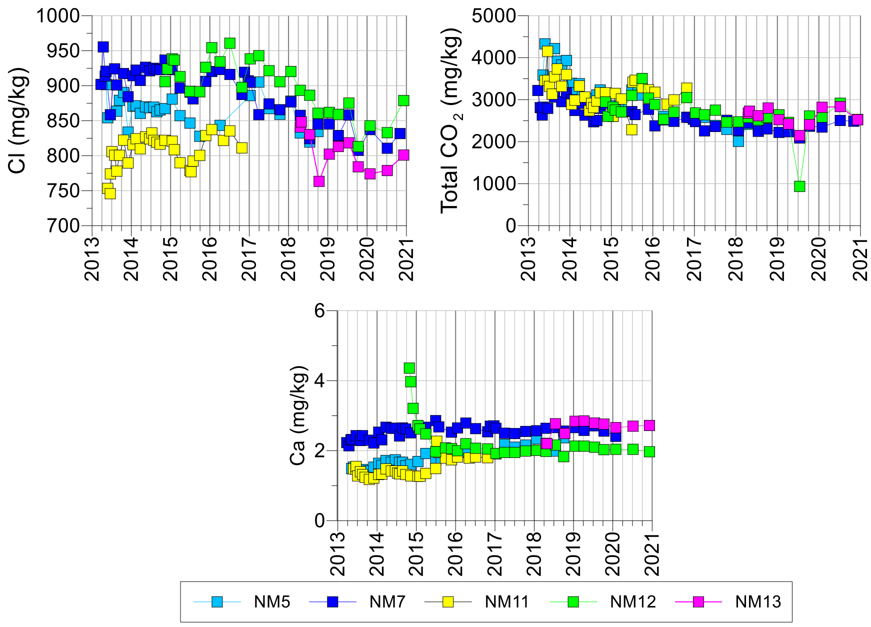

Figure 7: Chemical trends for the Ngatamariki production wells.

Calcite scaling has been observed in all Ngatamariki production wells, with the exception of NM7. Analysis of the calcite saturation index (CSI) for NM11 shows that in the early years of production the well was apparently undersaturated with respect to calcite (Figure 8). This is interpreted as most likely due to calcite being deposited in the wellbore and near wellbore formation, resulting in a reduction in the calcium concentration measured at the surface. The produced fluid in NM11 became slightly oversaturated with respect to calcite under boiling conditions once antiscalant dosing was started, suggesting calcite scaling within the wellbore had been inhibited or reduced.

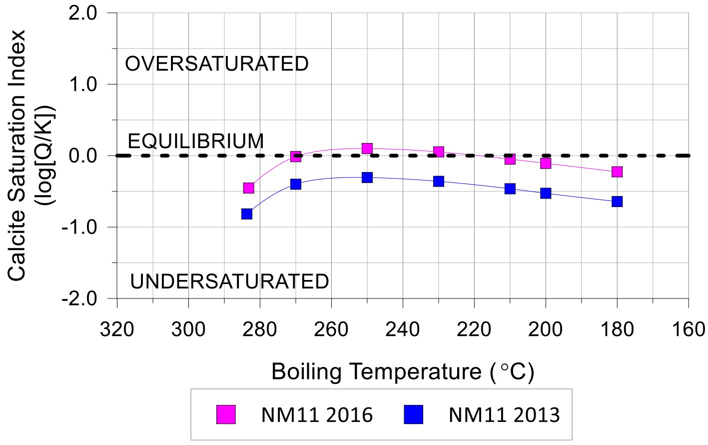

Figure 8: Calcite saturation index for NM11.

5 NM11 PERMEABILITY DECLINE MECHANISMS

Thus, the initial permeability decline is the main unexplained feature in the operational history of NM11. Four possible mechanisms for this decline have been proposed and are discussed below.

5.1 Calcite scaling due to ingress of marginal fluid

One possible mechanism for calcite scaling in the formation around NM11 is the ingress of marginal fluid. The presence of a potential downflow around NM11 area is inferred from the observed localized lower chloride concentration (Figure 11) and slightly lower temperature in NM11 (Figure 12). NM11 produced fluid with temperature of 280 °C while NM7 and NM12 produce fluid with temperature >285 °C. The temperature profile of NM11 is about 1 °C lower than the nearby NM5 although geographically, NM11 should be closer to the upflow than NM5. In addition, NM13, which was drilled to produce from the reservoir area between NM7 and NM11, is producing fluid with temperature almost 5 °C lower than NM7. This implies that the cooler fluid affecting NM11 is also affecting NM13 to some degree. In the conceptual and numerical models, the dilute, cooler fluid is inferred to be downflowing through one of the faults in the NM11 area.

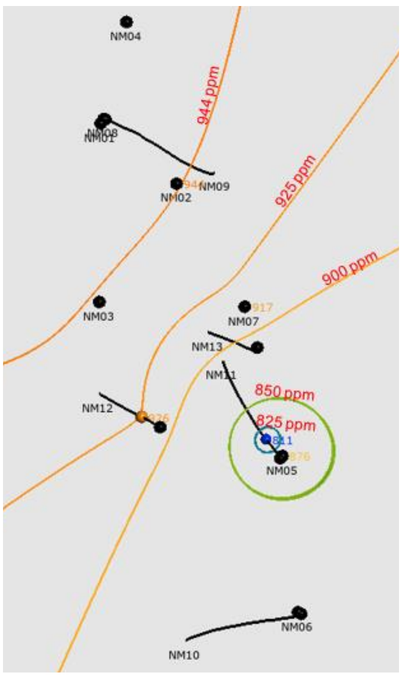

Figure 9. Ngatamariki chloride distribution in natural state showing a localized more dilute chloride around NM11.

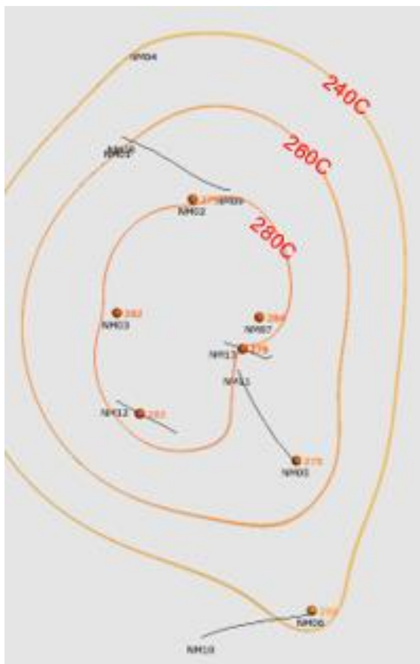

Figure 10. Contour maps of Ngatamariki natural-state temperatures at -1500mRL showing localized slightly lower temperature around NM11.

There are three potential sources of more dilute fluid in the NM11 area, the Whakamaru aquifer, the cold intermediate aquifer, and the shallow groundwater aquifer. Mixing of the shallow and intermediate aquifers with reservoir fluid using Geochemist's Workbench (GWB) did not produce a fluid that was oversaturated with respect to calcite. The final fluid that could dilute the produced fluid in the NM11 area was that from the Whakamaru aquifer, which is hosted within the Whakamaru Group Ignimbrite (Figure 2) and located above the deep clay cap. As no monitoring wells tap the Whakamaru aquifer, the composition was inferred from the downhole sample from NM11 in 2017. This fluid is thought to represent the aquifer fluid due to a casing break at a depth that would tap the Whakamaru aquifer. One complicating factor is that the downhole sample appears to be significantly oversaturated with respect to calcite. This is likely due to dissolved gases being lost during sampling. As such, CO_2 was added back to the fluid until it reached equilibrium with respect to calcite at 152 °C, the temperature of the Whakamaru aquifer. The equilibrated Whakamaru fluid was mixed with reservoir natural state fluid compositions from NM7, NM12 and NM13. For each example, Whakamaru fluid was added until the chloride of the mixed fluid matched the average chloride concentration in NM11 from 2013. The results are shown in Table 3.

Table 3: Mixing ratios required to reach NM11 chloride concentration.

Parent Fluid	% Parent Fluid	% Whakamaru Fluid	Saturation With Respect To Calcite
NM7	82.6	17.4	Oversaturated
NM12	85.5	14.5	Equilibrium
NM13	95.2	4.8	Undersaturated

While this simple mixing model suggested that ingress of marginal fluid from the Whakamaru aquifer has the potential to cause calcite deposition in some scenarios in the NM11 area, the extent over which it could cause deposition was not clear. TOUGHREACT was used to investigate the potential for permeability damage in the deeper feedzones of NM11. A simple 1-D radial model was used to simulate a downflow into the reservoir but there was minimal impact in terms of permeability damage over a period of 5 years. This suggests that while mixing of the Whakamaru fluid with reservoir fluid can cause calcite deposition, the effect is spread out and would therefore not significantly affect permeability near NM11. These results are consistent with the fast kinetics of calcite equilibrium, with the mixed fluid quickly reaching equilibrium through calcite deposition. This results in a small amount of calcite being distributed through the formation to maintain equilibrium as the marginal fluid is heated and mixed with reservoir fluid. The results from the basic TOUGHREACT modelling suggest it is unlikely that the permeability damage around NM11 could be caused by marginal fluid ingress over such a short period of time.

5.2 Calcite scaling below flash depth

Calcite scaling is typically induced by flashing in the wellbore, which causes CO_2 gas to be released from solution and the pH of the water phase to change. The point at which this occurs in the wellbore is typically taken as the flash depth. Total gas pressure (TGP) can also be considered when determining the point at which gas is first exolved from the water phase (Akin 2019). Total gas pressure is the sum of the partial pressures of all dissolved gases and the saturation pressure of water at relevant temperature and chemistry. Comparison of the pressure at the flash depth with the TGP for Ngatamariki production wells shows that the risk of scaling is deeper than the flash depth in all wells, particularly NM5 and NM11. This is consistent with scale observations in NM5, where calcite scaling was tagged below the inferred flash depth. The TGP derived flash depth in NM11 suggests calcite scaling could be expected up to 160 m below the inferred flash point.

Table 4: Comparison of pressure at deepest possible flash depth and estimated total gas pressure for Ngatamariki production wells.

Well	Pressure at flash depth (bara)	Flash depth (m)	TGP (bara)	TGP derived flash depth (m)
NM5	65.7	1500	80.4	1650
NM7	76.5	1250	81.5	1310
NM11	65	1250	79.3	1410
NM12	73.7	1120	77.6	1180
NM13	72.2	1050	75.2	1100

The estimated deepest flash depth based on TGP, as it is estimated from the point in a wellbore model where the fluid reaches this pressure, however the wellbore model does not account for all gases, so the calculation beyond this point does not account for the pressure drop changing due to the transition to two phase flow. It is likely the TGP derived flash depth may be slightly deeper than estimated, as if the wellbore model could account for TGP, there would be slightly less pressure drop from the wellhead to feedzones (due to a lower average density), so pressure at feedzones could be reduced.

It is clear from the data displayed in Section 3, that the pressure in the well dropped considerably once produced (Figure 5). This lowered the flash depth and consequently also lowered the TGP derived flash depth. Analysis of the data suggests that calcite scaling in NM11 should have been expected below the flash depth, which gradually lowered during production, depositing more scale further down the well. However, it is difficult to explain how calcite could have been deposited in the deeper feedzones, as evidenced by the permeability decrease from the December 2013 PTS (Figure 6). Therefore, calcite scale in the near wellbore formation of NM11 is a consequence of the pressure drop upon production but does not fully explain the declining performance of the well.

5.3 Permeability decline due to thermal expansion of rock

Injection wells at Ngatamariki show a strong stimulation effect when cold water is injected into hot rock. It is possible that NM11 had some opposite effect following drilling – the well appeared to take more than 6 months to reach a maximum enthalpy. If the initial permeability was a 'stimulated' state and the temperature recovery reversed this, a permeability reduction could be expected, but the magnitude seems large for a small temperature change. It will be dependent on the thermal expansion of rock and fracture dimensions, which is difficult to quantify. Cold quench PTS surveys done during the 2015 and 2016 acidizings appear to show a higher permeability than the hot flowing surveys. Siega 2014 showed a temperature increase of approximately 10°C in the Tahorakuri formation could decrease injectivity by 20% in injection wells in the Wairakei – Tauhara geothermal field.

5.4 Permeability decline due to unstable reservoir formation

Another possible mechanism for the production decline observed is formation collapse. Indications of unstable formation (i.e. zones of washouts) have been noted below the casing shoe of NM11. Formation fill could accumulate behind the perforated liner or fine grains could collect and block up feedzones. Minor feedzones are identified within the zone of unstable formation and it is possible that fluid movement could have further weakened the formation and cause the rock to erode and collapse on itself to close the fluid pathways.

6 CONCLUSION

NM11 is an inactive production well at Ngatamariki geothermal field drilled 3km deep. It is a large diameter well with an 18-5/8" production casing. The well was first flowed in 2013, initially providing approximately 1000t/h. In the first period of production, the well declined rapidly. Calcite scale was detected in the wellbore 10 months after beginning production, and the well was ultimately rendered unproductive following two acidizing attempts. Geological, reservoir engineering, and geochemical data indicate that the final unproductive state of the well is a result of a combination of factors:

- The initial decline of the well was due to a permeability reduction across all feedzones of roughly 60%.
- Calcite scaling within the wellbore caused further decline.
- The two acidizing attempts potentially weakened casing integrity which led to the perforated liner failure that resulted in a wellbore blockage above the well's major feedzones.
- New modelling shows that calcite scale can begin to form much lower than previously understood due to exsolution of dissolved gases prior to the expected flash depth.
- The design of the well (18-5/8" production casing) resulted in lower pressures in the wellbore (though higher flowrates) than would have occurred in standard design wells, further deepening the flash depth.

While most of these factors are now understood and can be avoided in the future, the cause of the initial permeability decline is not fully known. Shallow feedzones could have been affected by scaling in the formation, however this is not believed to be the case for the deeper feedzones in the well. Marginal fluid mixing has previously been a consideration, however geochemical modelling shows that while mixing of the Whakamaru fluid with reservoir fluid can cause calcite deposition, the effect is likely spread out and would therefore not significantly affect permeability near NM11 in the timeframe observed to fully explain the decline. Minor thermal expansion as the well slowly heated following drilling could have contributed to the closing of fracture apertures, reducing permeability, but the magnitude of permeability loss is higher than would be expected for this mechanism.

7 ACKNOWLEDGEMENTS

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