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Modelling of Scaling in a Tauhara Production Well

Emily Clearwater, Jose (Jun) Seastres Jr., Juliet Newson and George Mulusa

Department of Engineering Science, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

emily.clearwater@auckland.ac.nz

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ABSTRACT

The nature of output decline in Tauhara well TH06 has been investigated using a numerical simulation. The scaling of the well is thought to be due to a combination of deposition at the flashpoint in the wellbore and deposition within the formation at the major feed zone. The numerical model aims to confirm the possibilities of formation scaling.

A preliminary 1-D radial kinetic TOUGHREACT model representing the major feed zone was constructed and production simulated using chemical and production field data as input. The model was then simulated for a number of years under a production scenario, and changes in mineral abundance observed. Calcite, illite, pyrite, quartz and epidote were all shown to be oversaturated and had volume fraction changes large enough to influence the porosity and hence flowrate and output of the well. More modelling is required to improve the models match to the true mechanisms driving the calcite deposition.

1. INTRODUCTION

The Tauhara geothermal field is part of the Wairakei-Tauhara geothermal system, located in the central North Island of New Zealand (see Figure 1).

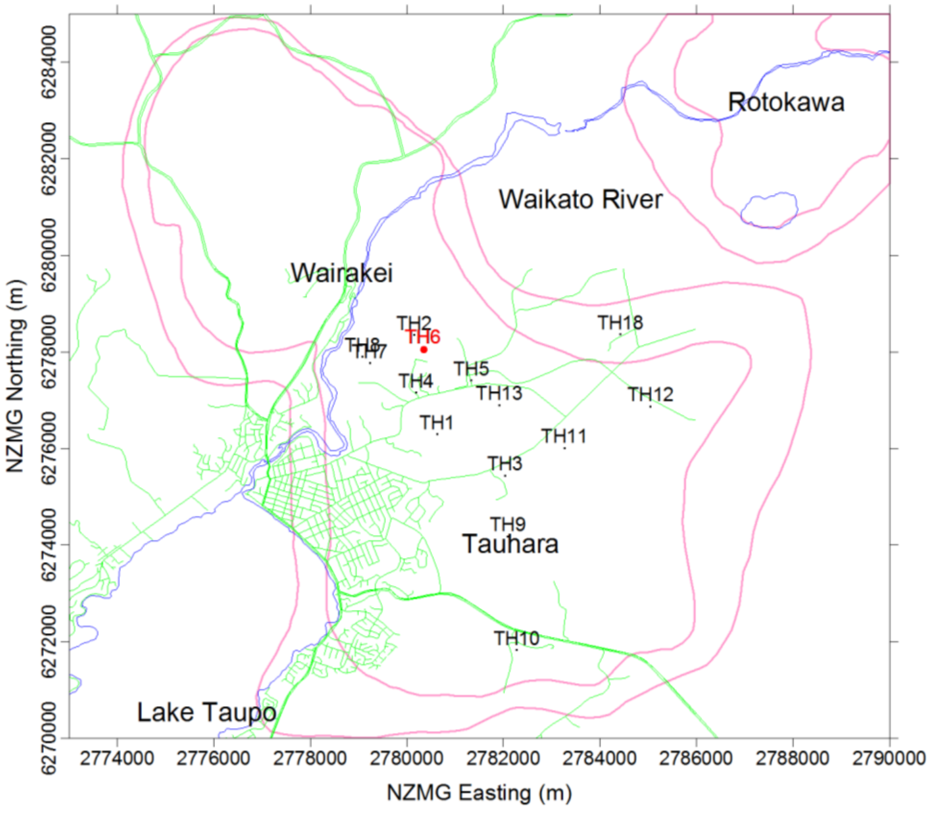

Figure 1: Wairakei-Tauhara geothermal Field, with Rotokawa nearby in the north-east. Pink lines represent resistivity boundaries, green lines roads, Tauhara wells are shown in black and well TH06 is shown in red.

The well of interest in this study is TH06, a production well used for industrial heat supply. Since the well was put onto production, annual workovers have been required to maintain production flows. A detailed review of the acidizing history and eventual success at returning TH06 to initial productivity is given in Helbig *et al*., (2011). Uncertainty about the actual reservoir processes affecting well output highlighted the need for further study on possible mechanisms for well decline. A short overview of the wells properties and performance is given in this work, followed by a description of the modelling study carried out to ascertain whether scaling may be occurring within the formation. The aim of this work is to investigate the initial reservoir condition, to see whether scaling in the near-well zone of the reservoir was likely to occur and hence influence wellbore output.

2. FIELD DATA

2.1 Geology

TH06 was drilled in 2005 as a vertical well and is used to deliver steam to the nearby timber drying facility. The well is cased to 596m and reaches 1011m total depth. The stratigraphy of the area is described in detail by Rosenberg et al. (2010), and only a brief description is provided here. Figure 2 shows the stratigraphic log for TH06. From the bottom of the well at 1011m depth to 380m depth is Waiora Formation, a pyroclastic deposit variously consisting of non-welded ignimbrite (Wa1) and mudstone and siltstone sediments intercalated with pumice-lithic breccia (Wa3-4). This is overlain from 380m depth to 305m depth by a coarse pumice-lithic rhyolite breccia (Te Mihi Breccia). The Huka Falls Formation overlies this from 305m depth, consisting of a bed of unconsolidated pumiceous sediments to 265m depth, overlain by mudstone, sandstone and siltstone to 140m depth. Above this lies the Oruanui Formation, a pumice-rich volcanic tuff, to 45m depth. From the surface down to 45m depth surficial deposits related to the 1.8ka Taupo Eruption are present.

Information from well completion tests shows one minor and two major feedzones at 625m, 850m and 930m respectively, all located within the Waiora Formation

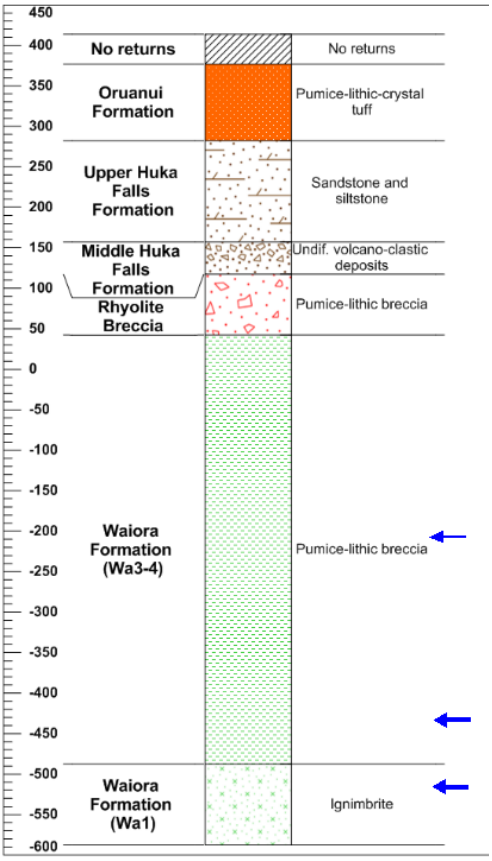

Figure 2: Stratigraphic well log for TH06 with feedzones indicated by arrows..

The mineralogy of the reservoir rock (in this case the Waiora Formation) has been significantly altered due to interaction with hot geothermal fluids. This alteration is dependent on permeability, temperature, pressure, initial composition of the rock and initial composition of the geothermal fluid. Hence, the locations and abundance of resulting alteration minerals gives insight into reservoir processes, temperature and permeability indications and scaling potential (Browne, 2010). The relative proportions of alteration minerals encountered at the feed zones of TH06 are given in Table 1.

Table 1: Geological well log data for TH06 feedzones (units are %).

Feed Zones (mCHF)	Formation	Clay (other than Illite)	Illite	Chlorite	Calcite	Epidote	Pyrite	Quartz
605-630 (minor)	Waiora Formation	10	20	15	20	ND	10	25
815-850 (major)	Waiora Formation	ND	10	30	20	20	10	10
925-930 (major)	Waiora Formation Ignimbrite	ND	10	25	10	25	15	15

The alteration minerals present indicate that the fluid in the rock is alkali-chloride type water. The occurrence of epidote indicates a reservoir temperature of 250°C or higher. This information also provided the initial mass fractions of minerals for the reactive modelling. However, it is important to note that the occurrence of these minerals in the well logs shows they were deposited previous to the wellbore drilling, within a potentially different reservoir condition, and hence may not be at equilibrium with the current reservoir fluid.

2.2 Well and production information

Pre-production data for TH06 consists of completion tests, shut-in temperatures and warm up tests. Completion test results give indication of feedzone locations. Shut in temperature profiles give the best approximation of pre-drilling reservoir conditions. Warm up test data indicates pressure gradients.

A shut-in temperature profile from 2006 (well closed for 3.5 months) is shown in Figure 3(a), indicating the temperature at the feedzones to be ~250°C. The main feedzone location is at 850m and 930m, with a minor feed at 625m (Figure 3(a)), the feeds are liquid fed and original fluid enthalpy is ~1100kJ/kg. Reservoir conditions at the major feed are 59 bar. Pressure data over time is shown in Figure 3(b). The minimal pressure drop seen indicates a sufficient amount of recharge to support the extraction rates from the well.

While on production, wellbore boiling led to calcite deposition in the wellbore. Go Devil runs, pre-and-post workover output tests (described further below), and camera runs indicate the regions of calcite deposition within the wellbore to be mainly occurring above the flashpoint (located above the shallow feedzone) in the wellbore. Locations of major scaling found in TH06 from 2006-2008 are shown in Figure 3(a). Go Devil runs from 2009 onwards indicate deposition at deeper intervals (923m and below) as well as within the major feed zone. Samples recovered during workovers consist mainly of calcite (~>90%) mixed with formation cuttings.

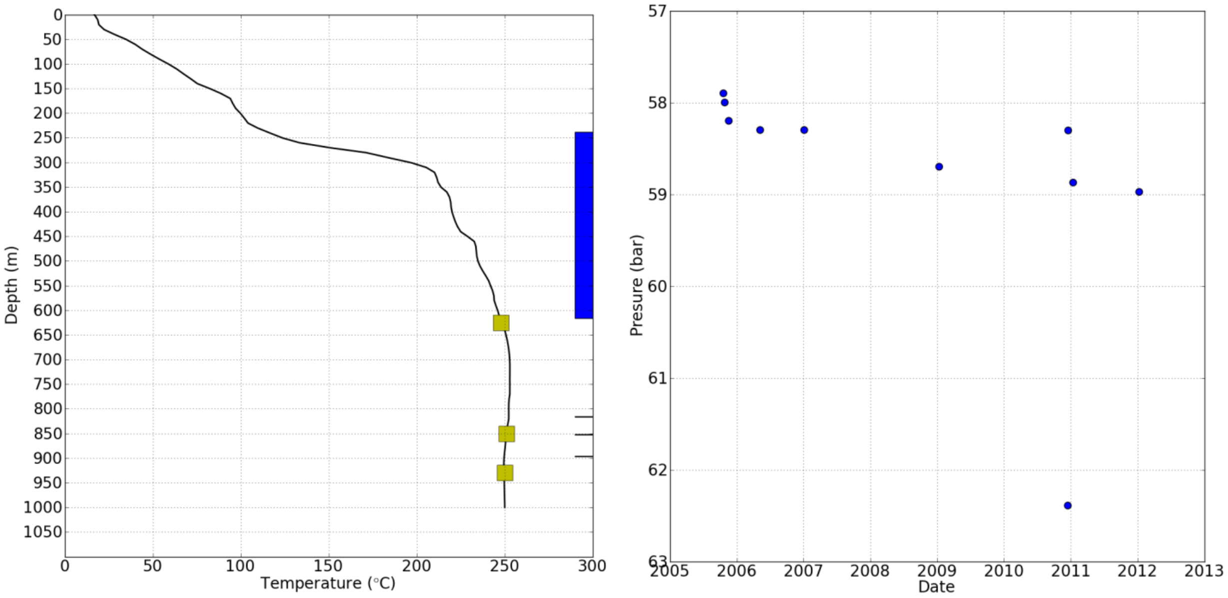

Figure 3: (a) Temperature, feedzones and scale locations. The yellow squares indicate feed zone locations, and blue bars wellbore scaling sites (left); (b) Pressure control point data for well TH06 (right).

Production data for TH06 consists of fluid enthalpy history, output test data, and workover information. This is shown relative to time, in Figure 4(a), and output testing results are given in Figure 4(b).

The well was output tested in May 2006. Output tests in the following January 2007 showed an output decline (Figure 4(b)). A coiled tubing workover and acidizing in November 2007 improved the output, but had a very minor effect on enthalpy.

A mechanical workover in January 2009 increased the well enthalpy, but output testing two months later showed that the well output had declined.

Further mechanical workover (January 2010) did not have an effect on enthalpy, which was declining. A workover plus acidizing in December 2010 appeared to have arrested the decline.

A conclusion from the above data is that the coiled tubing acidizing (known to be less effective at removing scale in the wellbore as drill pipe acidizing) must have allowed acid to reach the deeper hotter feedzone, but not removed all scale in the wellbore between the deep feedzone and the shallower feedzone. Hence, when the mechanical workover was then performed in January 2009, the connection to the surface was re-opened for the deep reservoir allowing the hot fluid to be mixed with the shallower feed and restoring original enthalpy.

It is also pertinent to note that the shallow feed has a natural state temperature similar to that of the deep feed. In order for this to align with the conclusion above (that while the wellbore scaled up the shallow feed dominated the output), some other mechanism is also working to reduce the enthalpy from the shallow feed. Falling enthalpy coupled with reduction in chloride (as seen in TH06 field data) is an indication of increasing dilution of the discharge fluid from a cold water source (Grant *et al.,* 1982). Hence, there must also be some shallow mixing occurring at the shallow feed with another fluid, generating the cooler ~940kj/kg output enthalpy.

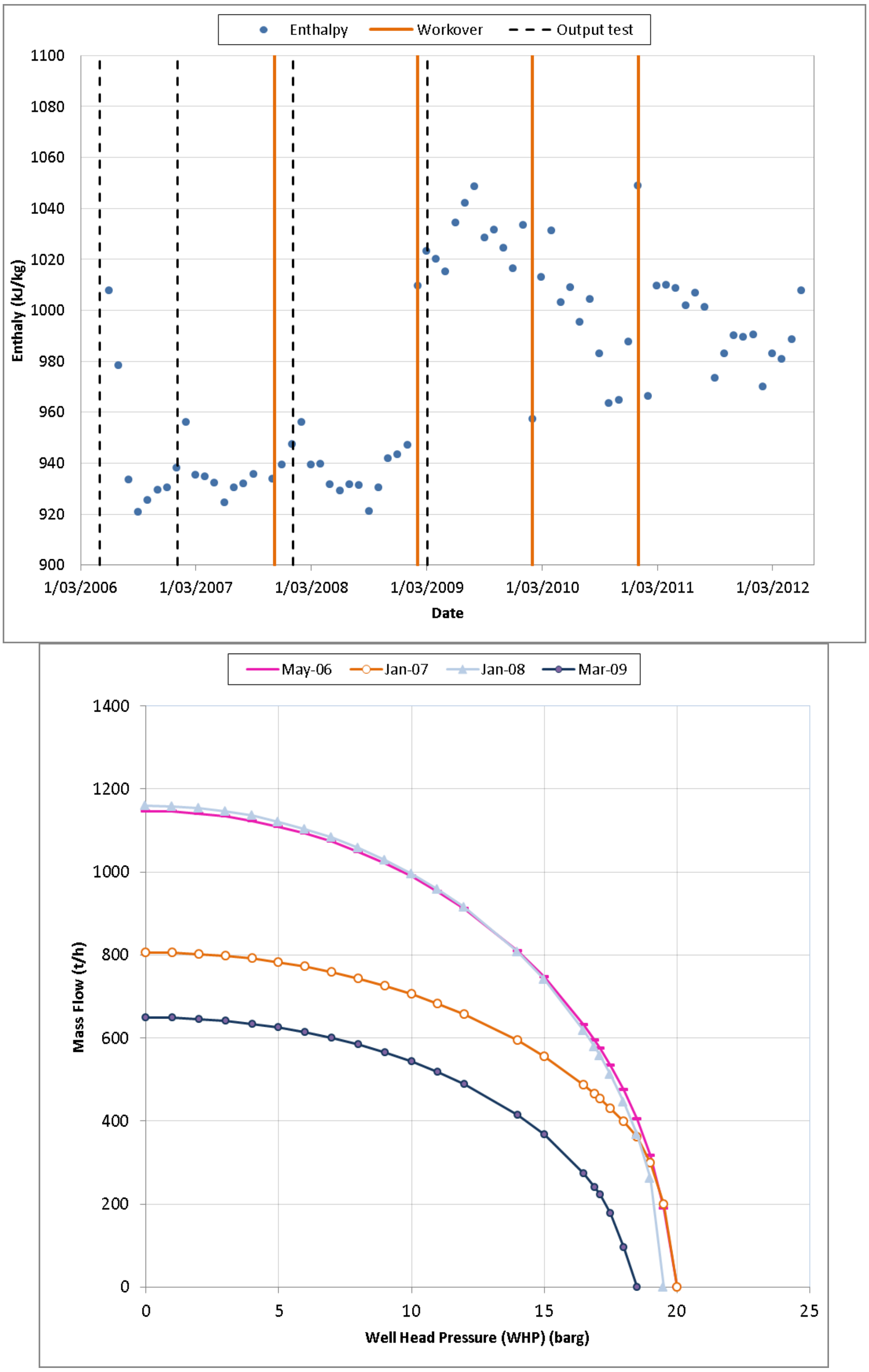

Figure 4: (a) Changes in fluid enthalpy for well TH06, with timing of workovers and output tests indicated (top); (b) Output test profiles (bottom).

Productivity and injectivity have been the main indicators used to determine successful workovers and acidizing for well TH06. A complete description of all discharge test results are described in Helbig *et al.,* (2011); only a subset of the relevant output test results for the period of interest are shown in Figure 4(b). Output curves over the 2006 to early 2009 period show the reduction in productivity over time, and restoration to original productivity after the initial coiled tubing acidizing. Unfortunately no output test data is available for the time period between the coiled tubing workover in 2007 and the 2009 workover. However, it can be seen in

Figure 4(b) that the coiled tubing workover with acidizing restored the wells performance to its original state, whereas the mechanical workover in 2009 did not.

The behavior over 2006 – early 2009 is the focus of this preliminary study; why did the acidizing in 2007 not improve the enthalpy of the fluid, but the mechanical workover in 2009 did?

2.3 Chemistry

Steam and water samples collected during output tests are available for well TH06. Data from 1/6/2007 is presented in Table 2.

Table 2: Water and Gas chemistry for TH06 used in modelling the reservoir fluid.

Date	WHP (barg)	HT (kJ/kg)	TMF (t/h)	Steam Collection Pressure (barg)	Gas concentrations in mmoles/100 moles								
					CO2	H2S	NH3	H2	CH4	N2	O2	Ar	He
1/06/2007	19.4	1109.3	247.5	17.5	242.2	11.3	1.5	0.39	5.3	6.1	0	0.07	0.002

Water Collection Pressure (barg)	TA (°C)	pH	Water concentrations in mg/kg														
			Li	Na	K	Ca	Fe	Mg	Al	Cl	F	Br	SO4	tHCO3	B	SiO2	H2Sw
18	18	7.71	7.9	722	116	6.7	0.08	0.04	0.64	1288	3.6	3.1	43	58	23	529	6.3

This data has been previously entered into WATCH (Arnorsson and Sigurdsson 1982); a software which, given output/surface chemistry measurements, calculates downhole/reservoir fluid chemistry and composition. The aim of using this software was to evaluate the aqueous species distribution of the geothermal waters at reservoir conditions. One step adiabatic boiling was performed from reservoir conditions (using the quartz geothermometer temperature as reference temperature) to various temperatures (simulating potential flashing in the formation caused by fluid withdrawal from the feedzone), to obtain a saturation index (SI) for each of the minerals found from the well log. The WATCH input and results are presented in Mulusa (2012), and the SI for various minerals are shown in Figure 5.

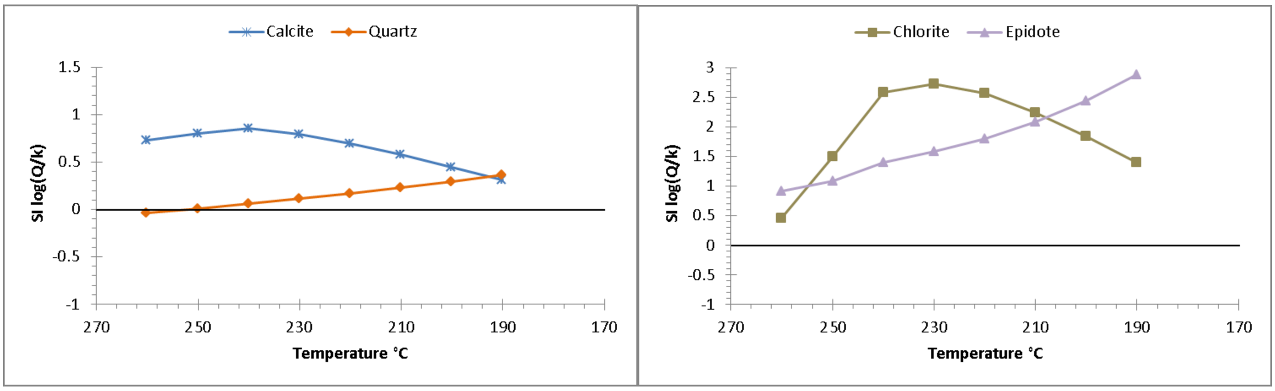

Figure 5: Mineral saturation index of the reservoir fluid as flashed from the feed zone (260°C) to 190°C by single stage adiabatic boiling.

Results from the 2007 chemistry show the fluid oversaturates with respect to all minerals except for quartz at temperatures above 190°C. Quartz is seen to oversaturate at temperatures below 250°C. The results shown here are similar to results from geothermal waters extracted at other times during the 2007 – early 2009 period, indicating that the alteration minerals present are oversaturated at the feedzone temperatures (~250°C). The WATCH output gives an ion balance for the 2007 chemistry to be -10.3%, so the chemical analysis is not complete and this needs to be kept in mind when observing results.

As noted in Section 2.2, scaling samples extracted from TH06 were essentially purely calcite – the other alteration minerals present are from a different episode of deposition. Hence, although the other minerals are oversaturated, calcite is the mineral primarily affecting the well output. The mechanism of calcite deposition (depressurization leading to boiling and degassing/increase in partial pressure of CO_2) doesn't favor the precipitation of the other minerals. To gain further insight into feedzone conditions, it was decided to develop a more complete model coupling a flow simulator with the geochemical modelling.

3. MODEL DESCRIPTION

Because we wished to simulate the chemical scaling near the wellbore, a 1-D radial model was setup which represented the major feedzone and the reservoir beyond. The coupled modelling of fluid and heat flow, solute transport and reactive chemistry was performed using TOUGHREACT, a non-isothermal multicomponent reactive fluid flow and geochemical transport simulator developed at Lawrence Berkeley National Laboratory (Xu et. al. 2004). Fluid production was simulated and deposition processes were observed.

The model consists of 50 elements within a single layer model 200m thick. The inner boundary of the mesh has a radius of 0.2m. Extending radially outwards from the inner boundary is a set of 30 blocks of equal radial thickness (0.01m), then 20 blocks which increase in radial thickness logarithmically, with the most outward block having a radius of 2000m. This grid is shown in Figure 6. Uniform initial reservoir conditions of 59 bar and 250°C are applied to the model. The top and bottom boundaries of the model are closed, and a constant pressure and temperature boundary condition is applied to the most outward block.

Rock parameters are shown in Table 3. A productivity index for these reservoir parameters, which correlated to a mass flow rate of 60kg/s (average mass flow rate from field data), was found to be 1.4E-12, and this was applied to the innermost block (i.e. adjacent to the wellbore) as a well on deliverability.

Table 3: Model rock parameters.

Density	Porosity	Permeability	Liquid conductivity	Specific heat
2500 kg/m3	0.1	1.2E-12	2.5 W/m°C	1000 J/kg°C

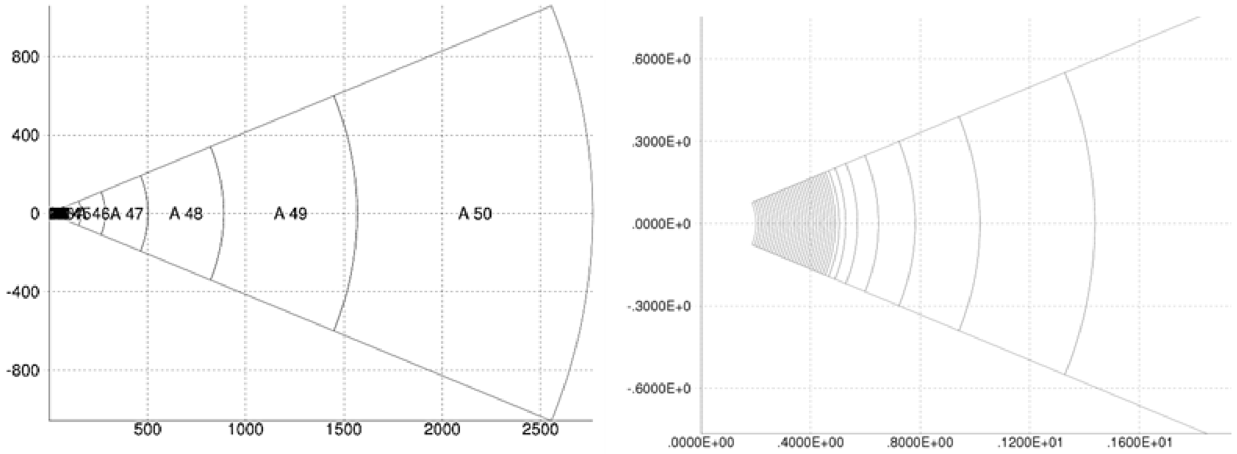

Figure 6: Sector of model grid – grid extends 360° radially. Full grid (left) and close up of block thickness near wellbore (right). Scale units are m.

Output test chemistry data (as mentioned in Section 2) was used as input for the numerical modelling in the present study. Because the time period 2006 – early 2009 was of interest, the water chemistry from the 2007 output test was used to define the initial water compositions of the geochemical system (Table 2), and mineral compositions as shown in Table 1 were used as initial conditions.

The thermodynamic database was populated from the EQ3/6 V7.2b database, as supplied with the TOUGHREACT executable, and activity coefficients applicability to geothermal conditions was confirmed by comparing values from geothermal geochemical modelling literature. Kinetic parameters for all minerals were taken from Palandri and Kharaka (2004), expect for pyrite parameters which were taken from Xu *et. al*. (2008). An equilibrium batch model was first simulated, in order to equilibrate the output fluid chemistry to reservoir conditions, and equilibrate the initial mineral compositions to the reservoir fluid. Minerals were then treated under kinetic constraints for the following production simulation.

4. MODEL RESULTS AND DISCUSSION

Results obtained from this initial exploratory simulation are shown below. Pressure and temperature across the model (extending radially outwards) are shown in Figure 7. The reservoir temperature remains constant, and there is a small amount of pressure drawdown, most likely due to the mass withdrawal rather than pressure drop within the reservoir due to flashing. The field data shows almost constant reservoir pressure in this region (Figure 3).

Mineral volume fraction changes over time are shown in Figure 8. All minerals except chlorite show oversaturation, which corresponds to the WATCH result for all minerals except chlorite. As discussed in Section 2.3, the current (2007 in this case) reservoir condition may no longer be favorable for precipitation of these minerals, especially as chlorite is most abundant at temperatures around 300°C (Ji and Browne, 2000). Due to the location of scale samples from the field data (found near the feedzone), we would expect the kinetics of deposition to be favoring calcite (scale was ~90% calcite). However, liquid saturation is remaining at 1.0 – no boiling is occurring in the model, although CO_2 gas is increasing a small amount. Bicarbonate ions are increasing, but calcium ions are decreasing, and the large abundance of epidote indicates that the kinetics of deposition displayed by the model is not favoring calcite deposition. However, a large volume fraction of calcite formation and some precipitation of the other minerals shows the model is representing the reservoir condition somewhat appropriately, but improvements to kinetic parameters need to be made in order to push the model towards the calcite deposition reaction.

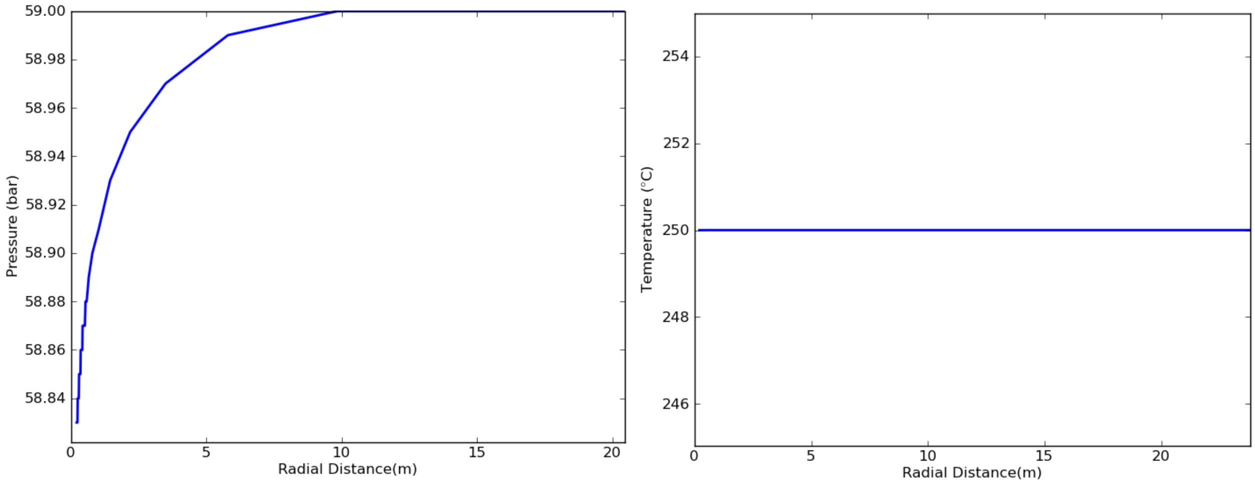

Figure 7: Reservoir pressure and temperature after ~0.4 years.

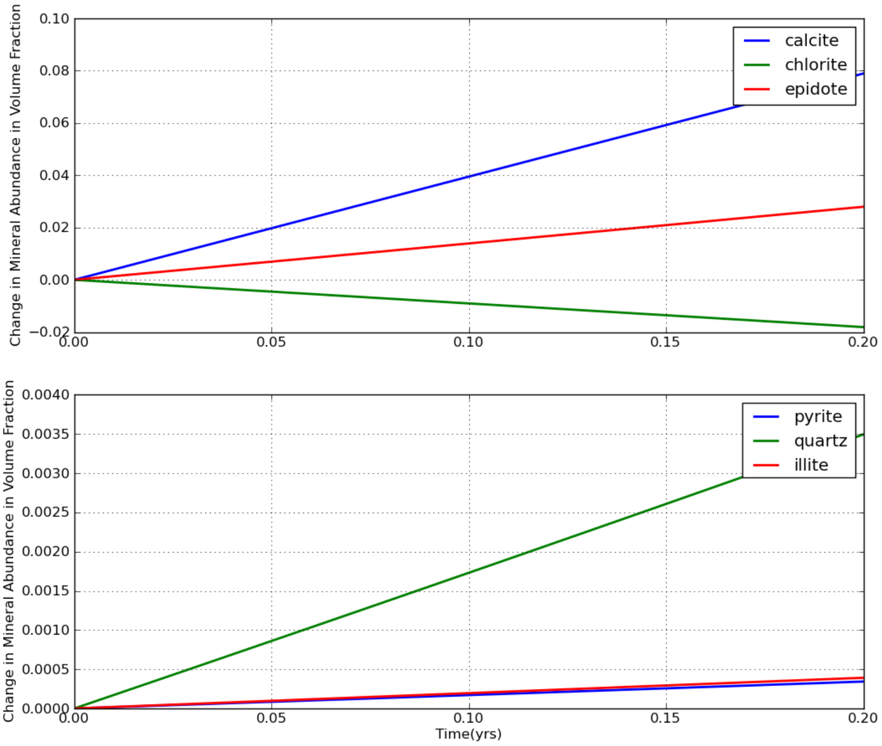

Figure 8: Mineral volume fraction changes over time.

Mineral volume fraction changes over distance are shown in Figure 9. It is clear that these depositions are occurring only very near the wellbore, rather than further away within the formation, giving an indication that the oversaturation is due to near-wellbore conditions rather than mass transport through the reservoir. The simulated CO_2 and H_2S gas volume fractions also change locally near the wellbore over time (due to the fluid withdrawal and pressure drawdown near the vicinity of the well), shifting the equilibrium position of relevant reactions, hence driving the localized changes. As mentioned above, boiling in the reservoir due to fluid extraction and increased CO_2 partial pressure would lead to calcite deposition, but the model shows the fluid is maintained at liquid phase; fluid withdrawal is not causing flashing in the formation/reservoir boiling. Also, if boiling was occurring, the kinetics should favor calcite primarily. The presence of these other alteration minerals in the simulation results indicates the scaling mechanism for this feedzone is driven by the chemical and physical condition rather than boiling. The presence of scale lower down in the wellbore (as mentioned in Section 2.2) from 2009 onwards is indicative of the flashpoint in the well shifting downwards, so boiling is most probably occurring near the feedzone, hence, improvements to the model are required.

Changes in porosity and permeability due to changes in mineral volume fractions throughout the simulation were monitored, but their effects on fluid flow were neglected. Including permeability feedback into the model incurred very long simulation run times. Also, the porosity/permeability correlation in geologic media is complex; different relationships would need to be explored and sensitivity analysis applied. Both of these points come at a large computational cost and hence changes in porosity due to changes in mineral volume fractions were only observed. As shown in Figure 10, the change in volume fraction of the minerals due to their oversaturation is enough to cause large porosity changes in a very localized area adjacent to the wellbore, indicating complete feedzone blockage after 3-4 months.

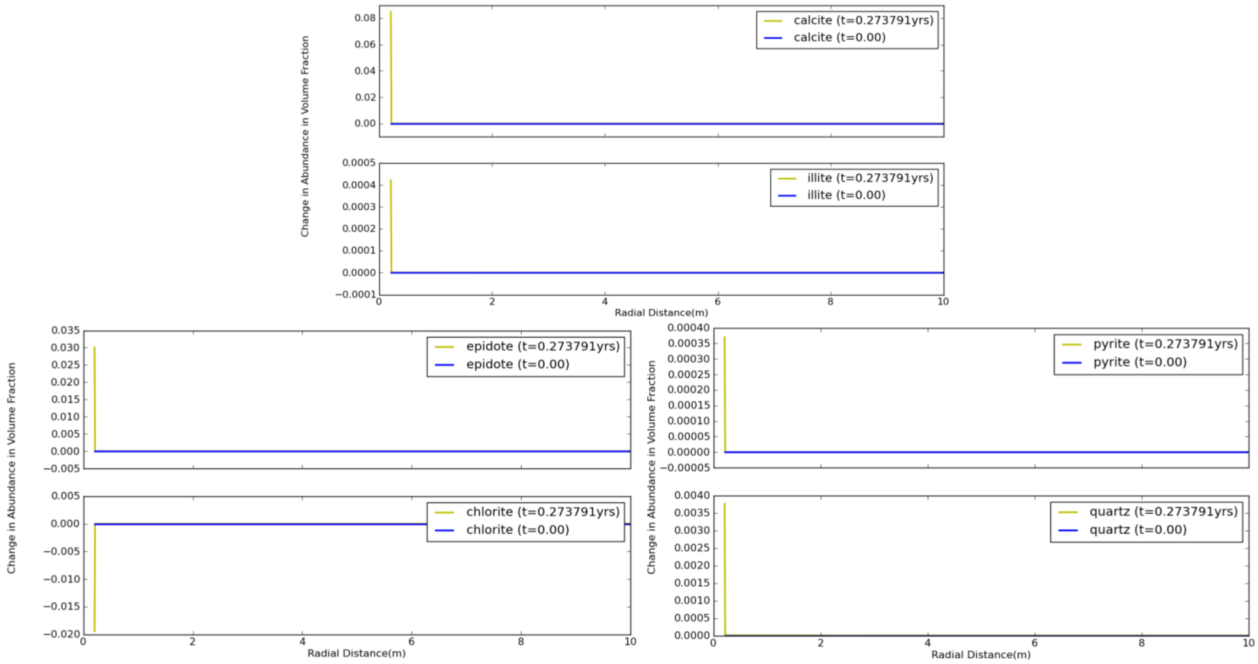

Figure 9: Change in mineral abundance (i.e. saturation) over radial distance.

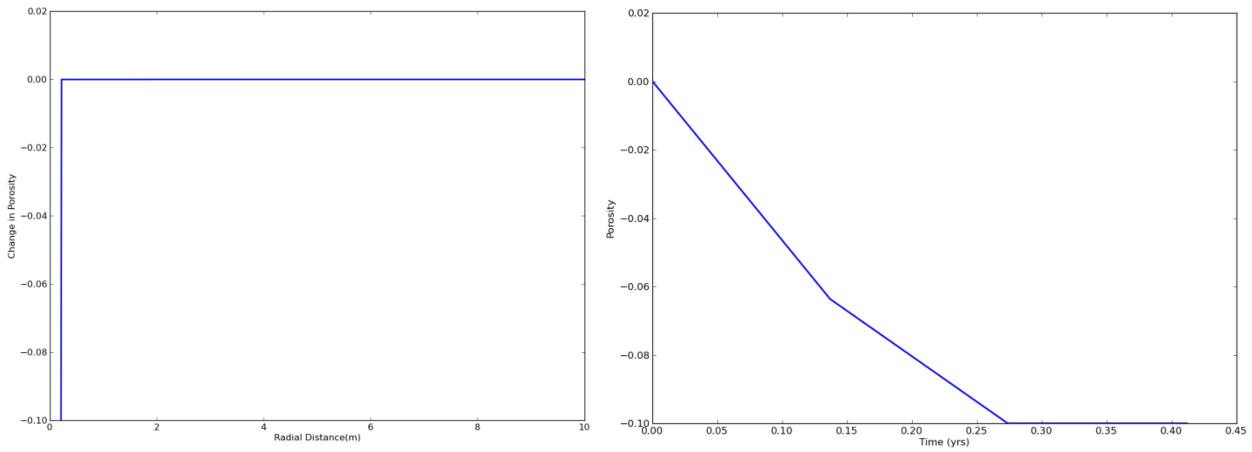

Figure 10: Change in porosity after 0.4 years over distance (left) and time (right).

Many uncertainties exist when trying to couple thermal and hydrological changes with reactive chemistry – kinetic data for mineral-water reactions, rock parameters for the reservoir representation and thermodynamic data of minerals, aqueous species and gases. For the reactive chemistry, thermodynamic data describing activity coefficients has large uncertainty at high temperatures, especially for solutions with high ionic strength. The ionic strength of the solution modelled in this work is low (<<0.5), so we have confidence in the thermodynamic data. The kinetic data however is subject to large uncertainty. Although values were extracted from a well-cited reference, Palandri and Kharaka (2004), who compiled and fitted a large number of experimental data reported from a large number of investigators, there is much uncertainty over rate constants and surface areas. Furthermore, the field data chemistry collection is a limited number of discrete samples, and has an ion balance of -4.5% (as calculated in the TOUGHREACT simulation). Hence, uncertainty analysis for these parameters should be addressed. With regard to the thermal and hydrological modelling, rock parameters were initially taken from the current well-calibrated Wairakei-Tauhara model developed at University of Auckland (see Yeh *et. al.,* (2010)). Those properties were then calibrated to deliver the actual mass flow rate. Hence, there is more certainty in these parameters, due to the history of accurate modelling of this field, but again, sensitivity regarding these properties should be performed.

However, as this is only a preliminary study to try and capture the main response of the reservoir system, the overall response of this model is of interest, and in that regard, this model is representing the system somewhat, but needs improvement. Under the 2007 chemistry conditions, results indicate that the major feedzone is scaling very near to the wellbore rather than further into the formation. The scaling is large enough to cause changes to porosity, and block up the feedzone.

For this work we have assumed that the wells early output chemistry reflects the major feed reservoir condition. The results from the numerical simulation reinforce the WATCH results – the mineral species at the major feedzone are oversaturated and precipitating. This scale is occurring in a very localized area of the formation right near the wellbore, which would lead to blockages for flow and a decline in well output. Hence, mechanical workovers of the wellbore would not improve the fluid enthalpy, but acidizing of the wellbore (which enters the formation) would – as was experienced in the field. The scale samples from the well blockages were purely calcite; the main well blockage reflects flashing within the wellbore, which is removed mechanically. This modelling shows blockages of calcite, epidote, quartz, pyrite and illite; occurring within the reservoir feedzone due to the chemical and physical conditions; removed through acidizing. The next step is to try and drive the model further towards calcite deposition. Further to this, a similar numerical simulation for other time periods should be performed, and correlation of well head pressure (where available) to reservoir scale, to see how the tendency for scaling is effected by wellbore conditions.

5. CONCLUSIONS

A preliminary study into the driving mechanism of scaling in well TH06 has been explored through a coupled flow and reactive chemistry model. Results using the 2007 chemistry data show mainly calcite but also epidote, quartz, pyrite and illite precipitation and porosity changes indicating a blockage of the major feed zone, localized around the wellbore.

REFERENCES

Arnorsson, S. and Sigurdsson, S.: The Chemistry of Geothermal Waters in Iceland. I. Calculation of aqueous speciation from 0 to 370°C, Geochimica et Cosmochimica Acta, 46, (1982), 1513-1532

Browne, P.; Introduction to Hydrothermal Alteration. Lecture notes for paper 601, University of Auckland Post Graduate Certificate in Geothermal Energy. University of Auckland, New Zealand. (2010)

Helbig, S.J., Bixley, P.F.. and Lee, S.G.: Successful Acid Treatment of a production well in the Tauhara Field, New Zealand, Proceedings, New Zealand Geothermal Workshop 2011, Auckland, New Zealand. (2011)

Grant M.A., Donaldson, I.G. and Bixley, P.F.: Geothermal Reservoir Engineering. (Academic Press Inc., New York, 1982), pp. 369.

Ji, J. and Browne, P.R.L.: Relationship between illite crystallinity and temperature in active geothermal systems of New Zealand. Clays and Clay Minerals, 48, 1, (2000), 139-144

Mulusa, G.: An assessment of calcite scaling in Tauhara wells TH06 and TH14, Master of Energy Project Report, University of Auckland, New Zealand (2012)

Palandri, J.L. and Kharaka, Y.K.: A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling, U.S. Geological Survey (2004)

Rosenberg, M., Wallin, E., Bannister, S., Bourguignon, S., Sherburn, S., Jolly, G., Mroczek, E., Graham, D., Bromley, C., Reeves, R., Bixley, P., Clotworthy, A., Carey, B., Climo, M. and Links, F.: Tauhara Stage II Geothermal Project Geoscience Report GNS Science Consultancy Report 2010/138 (2010)

Xu, T., Sonnenthal, E.,Spycher, N. and Pruess, K.: TOUGHREACT User's Guide: A Simulation Program for Non-isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Porous Media. Lawrence Berkeley National Laboratory, Berkeley, California 94720 (2004)

Xu, T., White, S.P. and Pruess, K.: Pyrite Oxidation in Saturated and Unsaturated Porous Media Flow: A Comparison of Alternative Mathematical Modeling Approaches. Lawrence Berkeley National Laboratory, Berkeley, California (2008)

Yeh, A., O'Sullivan, M.J., McDowell, J., Mannington, W.I., Brockbank, K,: An update on the modeling of the Wairakei-Tauhara geothermal system. Proceedings GeoNZ2010, University of Auckland, Auckland, New Zealand (2010)