MODELLING OF THE ROTORUA GEOTHERMAL FIELD INCLUDING CHEMISTRY

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ABSTRACT

The Rotorua geothermal field is situated at the southern margin of the Rotorua Caldera in the Taupo Volcanic Zone, New Zealand. The Rotorua system lies beneath a small city and has an abundance of natural features of great cultural, economic and scientific value. However from the 1950's onwards, intensive extraction of fluid and heat from over 900 shallow wells resulted in a decline of many surface features. In 1986, a bore closure programme was introduced and geyser activity and hot springs have rejuvenated progressively with some springs overflowing recently for the first time in over 30 years.

The chemical signature of surface thermal features and the discharge from wells within the Rotorua geothermal field has been recorded in various monitoring reports. These have great value as they not only give insights into the origin of the geothermal fluid and conditions at depth but also compositional changes can help to explain variations in surface activity.

A three-dimensional numerical model of the Rotorua system, UOA Model 4 (Ratouis *et al*., 2014), was previously developed to study the response of surface features to production and reinjection. Recently the transport of chloride and CO_2 was included to further constrain the numerical simulations. This model is designated as UOA Model 4a hereafter. Natural state and production simulation runs were carried out using the EWASG equation-of-state (non-isothermal mixtures of water, sodium chloride and a non-condensible gas) in the numerical simulator AUTOUGH2, the University of Auckland's version of TOUGH2. In addition to temperatures and surface heat and mass flows UOA Model 4a was calibrated with the available chloride data and CO_2 surface flux data.

INTRODUCTION

Background

The Rotorua Geothermal Field (RGF) underlies much of Rotorua City, with surface geothermal activity confined to three areas: Whakarewarewa/Arikikapakapa in the south, Kuirau Park/Ohinemutu to the northwest and Government Gardens/Sulphur Bay/Ngapuna to the northeast (Figure 1).

The RGF is unique in that it lies beneath a city and contains one of New Zealand's last remaining areas of major geyser activity at Whakarewarewa (Figure 1). The geothermal resource and features have a strong cultural significance in terms of Māori beliefs and customs (Neilson et al., 2010), economic value as tourist attractions and energy sources, and hold remarkable biodiversity (Acland, 2006).

First records of geothermal heat exploitation date from the 1800s (traditional use and fluid extraction from springs) and in the 1920s the first wells were drilled in the field to extract the hot water for domestic and commercial heating and bathing purposes. This caused only minimal disturbance to the resource. However from 1950 onwards, increasing demand led to a phase of intensive drilling and geothermal fluid abstraction from shallow bores and there were 500 wells by 1985 (Ministry of Works, 1985). Lack of regulations led to an erratic development of the field and, in the late 1970's a significant decline in surface geothermal activity was observed (Gordon et al., 2005).

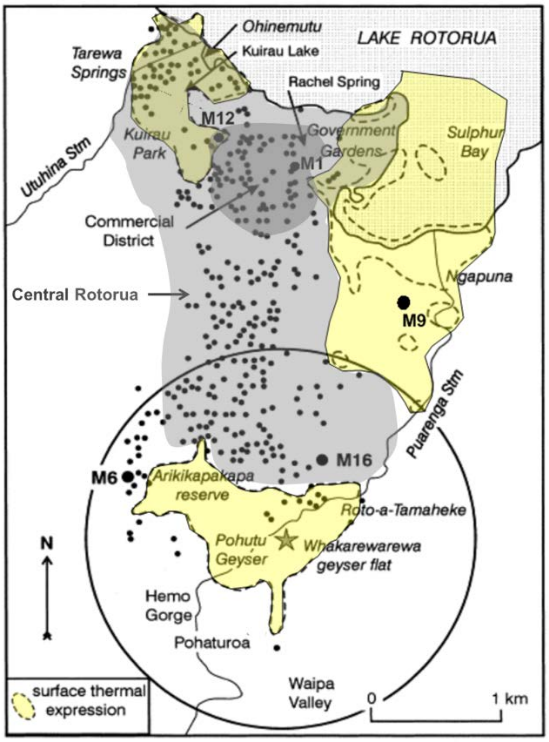

Figure 1: Surface features and distribution of geothermal and monitoring wells in Rotorua city in 1985 (From Scott and Cody 2000)

Increasing concern over the effect of geothermal fluid withdrawal on springs and geysers led to the closure of all bores within a 1.5 km radius of Pohutu Geyser (Whakarewarewa), closure of all government owned wells in Rotorua City and a royalty scheme was introduced to promote fluid reinjection into the reservoir rather than discharge to shallow soakage (Gordon *et al*., 2005). These time periods are generally defined as presented in Figure 2.

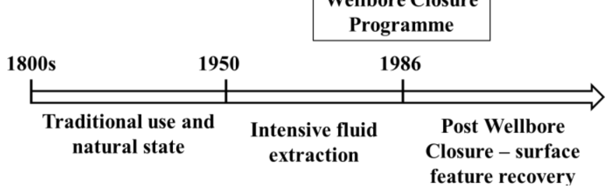

Figure 2: Historical timeline of the geothermal fluid production in Rotorua

Prior to and following the Well Closure Programme, geochemical data from springs and wells were collected to characterize the geothermal system. The present paper summarizes some of the major findings from these geochemical surveys and the role of field chemistry in the identification of reservoir flow patterns (upflow, boiling, recharge, etc.). The modelling work aims to match available chloride distribution data from geothermal bores (Stewart *et al*., 1992) and available surface CO2 mass flux (Werner and Cardellini, 2005). The current model is based on UOA model 4 which used the equation of state EOS3 for water and air (Ratouis *et al*., 2014).

1. GEOLOGICAL SETTING

1.1. The TVZ

Rotorua city lies within the Taupo Volcanic Zone (TVZ) in the North Island of New Zealand (Figure 3). The TVZ is a volcano-tectonic depression dominated by Quaternary rhyolitic and andesitic volcanism in which major extensional faults strike SW-NE (Wilson *et al.*, 1995). Accompanying the high volcanic activity is an extremely high natural heat flow, which induces large convective cells of hot rising fluid forming the geothermal fields. Surveys of surface features and resistivity surveys have delineated more than 20 geothermal fields within the TVZ (Bibby *et al*., 1992), one of which is the RGF (Figure 3).

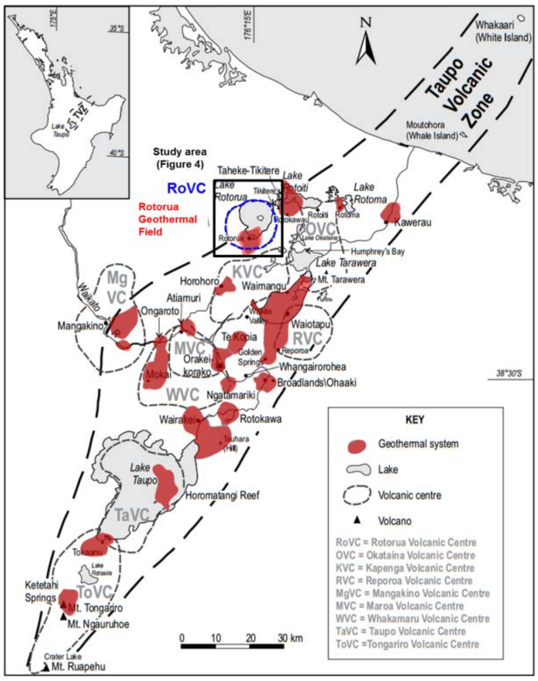

Figure 3: Location of the RGF (in red) within the Rotorua Caldera (in blue) (From Cody, 2007)

1.1. The Rotorua Geothermal Field

The RGF is located within the Rotorua rhyolitic Volcanic Centre at the southern margin of Lake Rotorua. It covers an area of approximately 18-28 km^2 as defined by electrical resistivity surveys (Bibby *et al*., 1992).

The Rotorua caldera is an asymmetrical, multiple-block collapse structure (Ashwell *et al*., 2013) formed during extrusion of the 220-230 ka Mamaku Ignimbrite (Spinks *et al*., 2005) (mauve in Figure 4). The southern part of the caldera was later affected by post collapse effusive volcanism around 200ka (Milner *et al*., 2003); the rhyolite domes of the Utuhina Group (purple in Figure 4).

A study of the morphology of the caldera and lava domes highlighted subsidence-controlling caldera faults (near N-S and arcuate) as well as SW-NE regional faults in the eastern and southern part of the resistivity boundary (Ashwell *et al*., 2013). Cole *et al*., 2005 pointed out that the morphology of the caldera was strongly affected by preexisting structures and Milner *et al*., 2003 noted that lava domes often extrude close or above caldera-forming faults that are used as conduits for the ascending magma

Later changes in lake levels left several terraces (tephra and alluvial sediments) across the Utuhina domes and Mamaku Ignimbrite (Ashwell *et al*., 2013): commonly called the Rotorua Sediment sequence (yellow in Figure 4).

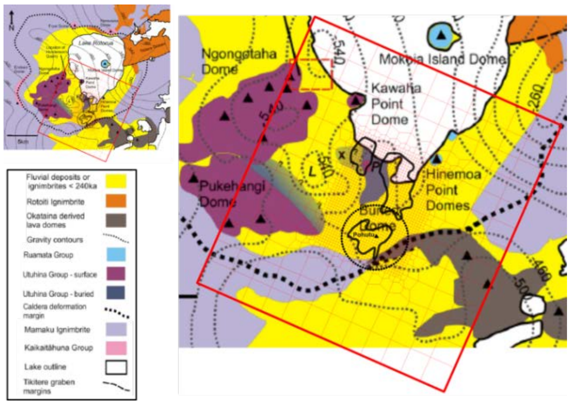

Figure 4: Geological map of the Rotorua Caldera (Ashwell *et al*., 2013). UOA Model 4 grid shown in red.

1.2. The Rotorua Geothermal Reservoir

Stratigraphy of geothermal bores within the RGF reveals that at reservoir depths (100-300m deep) the Mamaku Ignimbrite occupies the east and extreme south sections (Whakarewarewa and Ngapuna), while the Rotorua Rhyolite forms a north-south trending ridge comprising north (Kuirau Park) and south domes in the centre of the field. Both these units are capped by a sedimentary sequence which covers all but a tiny outcrop of the northern dome (Wood, 1992). The Buried Dome is bordered by a thick sedimentary unit to the west (Hunt, 1992).

2. GEOCHEMICAL STUDIES

Geochemical studies in geothermal system are commonly used to characterize the system, assess the quality of the resource and are an essential prerequisite to the development of a conceptual model. Changes of the chemical composition of geothermal bores and surface features may be used to monitor the field response to production and reinjection and give insights into the sustainability of the resource.

2.1. Chloride – Bicarbonate – Sulphate

Several geochemical surveys have been conducted as part of the Rotorua Monitoring Programme to describe flow patterns within the system and to gather reference values for comparison with future surveys. Chemical compositions of water collected in two consecutive campaigns are used in the present study: 1983-84 (Stewart *et al*., 1992) and 1989-1990 (Giggenbach and Glover, 1992). Here they are used to further calibrate the model and to assess the impact of the production and reinjection scheme, introduced in 1986, 3 years into the Wellbore Closure Programme.

The chemical compositions from 69 wells were gathered and compiled by Stewart *et al*., (1992) (Figure 5). The samples were then divided into three groups on the basis of their spatial distribution and chloride – bicarbonate – sulphate ratios (Figure 6).

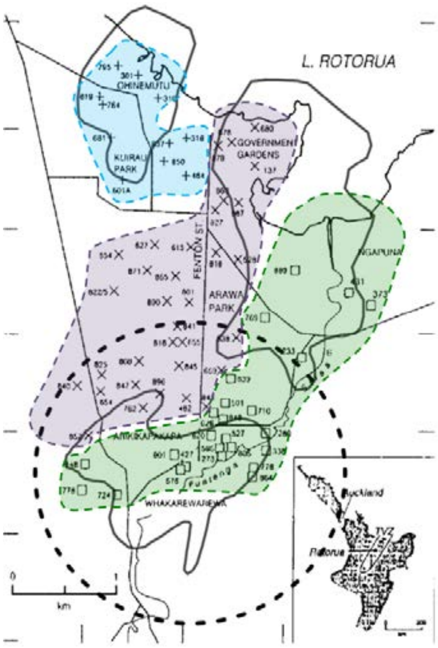

Figure 5: Location of sampling sites of the 1983-84 campaign. (Square represents East and South wells (ES), crosses North and West wells (NW) and pluses Kuirau Park wells) (Stewart *et al*., 1992)

The Eastern and Southern (ES) group has high chloride to bicarbonate ratio (> 80%) with low sulphate content, the characteristics of non-diluted mature geothermal waters (Figure 6). Kuirau park group has intermediate chloride − bicarbonate percentage (slightly above 50%) and low Sulphate concentration which indicate diluted mature waters. The North and West (NW) group has high sulphate content and transitional chloride to bicarbonate ratio (≈ 1/2) which indicates increasing degrees of dilution of geothermal fluid.

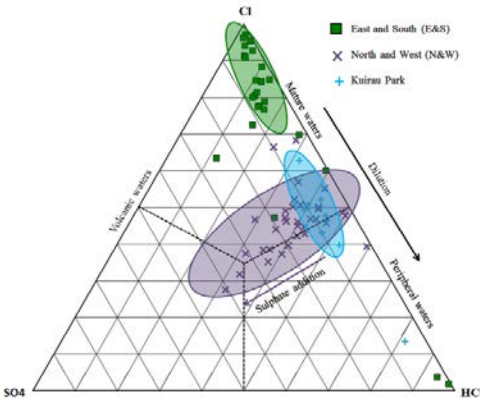

Figure 6: Chloride, bicarbonate and sulphate ratios for wells within the RGF. (data from Stewart *et al*., 1992)

The high sulphate content of the NW waters is expected to have resulted from oxidation of H_2S contained in the geothermal fluid by oxygenated water. Sulphate contours highlight an eastern sideflow of rainwater which penetrates the system from the western sedimentary unit between the two rhyolite domes, an area known as the Saddle (Figure 7). This is substantiated by a high tritium content which indicates rainwater recharge inflowing from this area (Stewart *et al*., 1992).

Low sulphate regions (ES and Kuirau Park) are identified as upflow areas of deeply sourced waters, assuming that the upflowing water prevents entry of oxygen bearing groundwater.

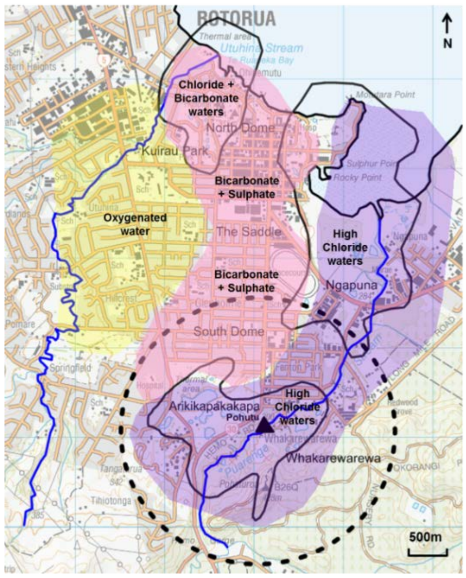

Figure 7: Simplified reservoir lithology and chemistry (Sedimentary rocks in yellow, rhyolite in pink, and ignimbrite in purple)

Boiling and mixing trends of the geothermal fluid are further defined by plotting enthalpy against chloride (Figure 8). The intersection of the projected steam loss and mixing lines determines the composition of a possible parent fluid (Stewart *et al*., 1992).

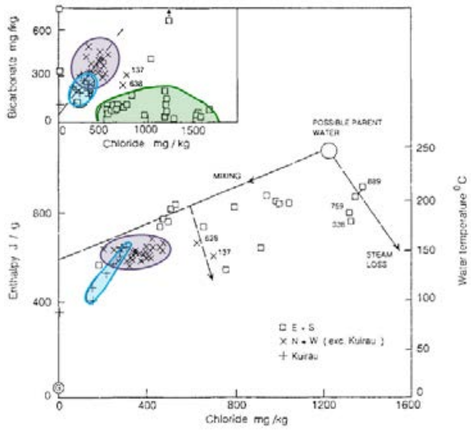

Figure 8: Enthalpy-chloride plot for Rotorua waters. Effects of steam loss and mixing are shown. The insert shows bicarbonate versus chloride (from Stewart *et al*., 1992).

The diagram supports the conclusion that East and South waters are the least modified geothermal water by dilution: water from wells RR889, 769 (Ngapuna) and 338 (Eastern Whakarewarewa) evolved due to boiling with minor dilution and those wells are located closest to the upflow. Waters from Whakarewarewa and NW wells are increasingly more diluted westward.

ES waters have generally low bicarbonate contents independent of the chloride content while NW waters show a general increase of bicarbonate with chloride content (insert in Figure 8). This trend was interpreted as follows: as the water is cooled by dilution the equilibrium concentration of dissolved CO_2 with respect to the rock decreases, while the actual CO_2 in solution is only slightly decreased. Hence the excess dissolved CO_2 begins to react with the rock to form HCO_3 and re-establish equilibrium (Stewart *et al*., 1992).

2.2. Surface CO_2 Flux

Measurements of CO2 flux were made at 952 locations between 2002 and 2003 and analysed using the sequential Gaussian simulation algorithm (sGs) by Werner and Cardellini (2005). Measurement spacing varied between 25-50 m and they were concentrated in Kuirau Park, Ngapuna, Government Gardens, Arikikapakapa and Whakarewarewa.

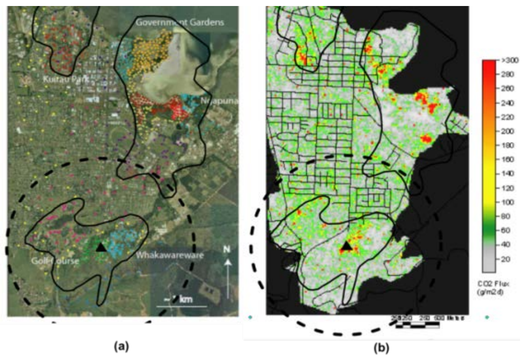

Figure 9: (a) Location and (b) magnitude of CO_2 Flux measurements across Rotorua city (from Werner and Cardellini, 2005).

The CO_2 flux measured ranged from not-detectable to 11535(g/day/m^2). The CO2 fluxes across the study area are spatially variable, but are higher above inferred upflow zones. The Ngapuna area displayed the highest fluxes, and the greatest number of high fluxes of any area in the study. High fluxes occurred to a lesser extent at Whakarewarewa, Arikikapakapa and Kuirau Park (all ≤ 3000 g/day/m^2). This confirms the idea that the Ngapuna area is likely to be the main upflow for the geothermal system as the greatest proportion of CO_2 is released from geothermal fluids through depressurization and boiling (Werner and Cardellini, 2005).

A spatially extensive zone of moderately high flux (350 g/day/m^2) was also observed in the Government Gardens region, along the mapped edge of the rhyolite domes. This area is not directly linked to any known primary upflow.

3. CONCEPTUAL MODEL

A conceptual model (Figure 10 and Figure 11) was built from observations discussed in previous sections and from temperature data (Ratouis *et al*., 2014). Some of its key features are summarized below.

Feedzones of the production wells are located within the Rotorua Rhyolite Dome and the Mamaku Ignimbrite and contain, respectively:

- Sub-boiling water with medium concentrations of chloride and bicarbonate (≈400 mg/kg). The upper part consists of pumiceous and fractured rhyolite of high permeability (Wood, 1992).
- Boiling, high enthalpy, high-chloride fluid (≈1000 mg/kg). Good fracture permeability (Wood, 1992).

Both formations are overlaid by the Rotorua Sediment sequence of low vertical permeability that acts as an aquitard and confines the geothermal fluid.

Well/spring chemistry (chloride, bicarbonates, sulphate) and surface CO_2 flux supported by the temperature distribution have highlighted three boiling upflows; along Puarenga Stream, Whakarewarewa (slightly diluted) and Kuirau Park (diluted). This generally supports the structural settings of the field with major near N-S (T&S, Ngapuna and Roto-a-Tamaheke), ring (ICBF) and SW-NE (Horohoro) faults near the southern edge of the caldera (Figure 10) which could act as preferential pathways for the rising geothermal fluid.

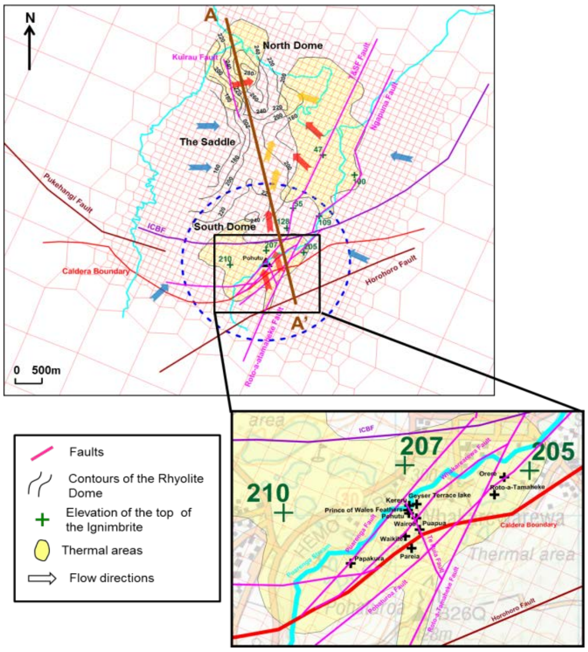

Figure 10: Geological and structural setting of the RGF and detailed map of Whakarewarewa (arrows show lateral fluid flow within the shallow parts of the RGF).

Temperature inversions as well as increasing HCO_3 content westward in wells across the Buried Domes suggest lateral fluid flow and mixing with heated groundwater. The fluid moves laterally from the faults within the faulted ignimbrite sheet and into the fractured rhyolite domes to the north from Whakarewarewa and westward from Ngapuna (Figure 11).

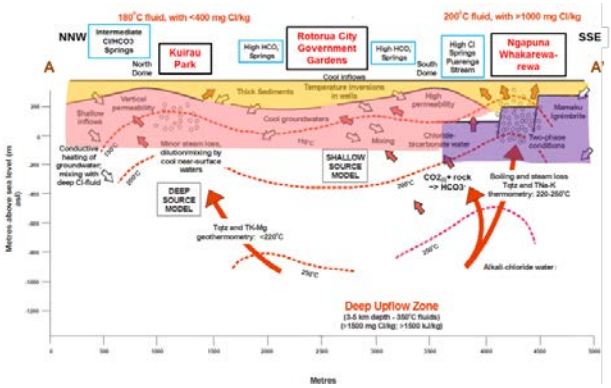

Figure 11: Cross section of the RGF conceptual model (location in Figure 9) (From Gordon *et al.*, 2005).

4. COMPUTER MODELLING

4.1. Previous Modelling Studies

Computer modelling together with a Monitoring Programme is one of the key tools for understanding and predicting the behavior of the RGF as any other geothermal field.

The first numerical model of the Rotorua system was developed in the 1980s and was used to assess the likely effects of the bore closure programme. The conclusions from this modelling study supported the implementation of such a programme (Grant *et al.*, 1985). Since, modelers from Industrial Research Limited (IRL) have set up two computer models, the first in the 1992 (Burnell and Young, 1992) and the second in the 2005 (Burnell and Kissling, 2005), called here IRL Model 2. It was developed to reproduce the behavior of the discharge features during the Wellbore Closure Programme and give insight into future possible production scenarios. IRL Model 2 includes chloride and some of its features will be compared to the model presented in this paper.

The latest model developed by the University of Auckland, UOA Model 4, provides a more detailed representation of the surface features and the very shallow unsaturated zone than previous models. UOA model 4 gives a good match to the natural state of the field and to the response to the 1986 Bore Closure Programme (temperature, pressure and mass flow transients) (Ratouis *et al*., 2014).

Transport of chloride and CO_2 was included in UOA Model 4a using the EWASG (Water – Salt – Gas) equation of state module (Battistelli *et al.*, 1997) in the numerical simulator AUTOUGH2 (Yeh *et al*., 2012), the University of Auckland's version of TOUGH2 (Pruess, 1991). It describes aqueous fluid of variable salinity as a mixture of water, chloride and non-condensible gas (here CO_2) (Pruess, 1991). With EWASG the shallow unsaturated zone is approximated as a mixture of water vapour and CO_2 (rather than air).

Incorporating chloride and CO_2 into the model provides more constraints over the system and complements the calibration process of matching temperatures, pressures, and surface heat/mass flows.

4.2. Model Specifications

General information about the model developed in this paper is summarized in the following table.

Table 1: Comparison of grid and model parameters.

Category	UOA Chloride Model	IRL Model 2
Grid area	12.4 km x 18.3 km	6 km x 8.5 km
Grid depth	2,000 m	570 m
Blocks	48,034	3,550
Layers	30	7
Minimum block size	125*125 m^2	125*250 m^2
Minimum block height	5 m	20 m
Orientation (angle to N-S)	23.7^0	0^0
Surface	Follows topography & lake bathymetry	Planar water table, 40m lower at the lake
Equation of State (EOS)	EWASG (Water, NaCl, CO2)	1 (pure water + chloride tracer)

The complex caldera collapse structures are also included in the model: explicit faults, down-faulting of the Mamaku Ignimbrite, the rhyolite domes (Figure 12).

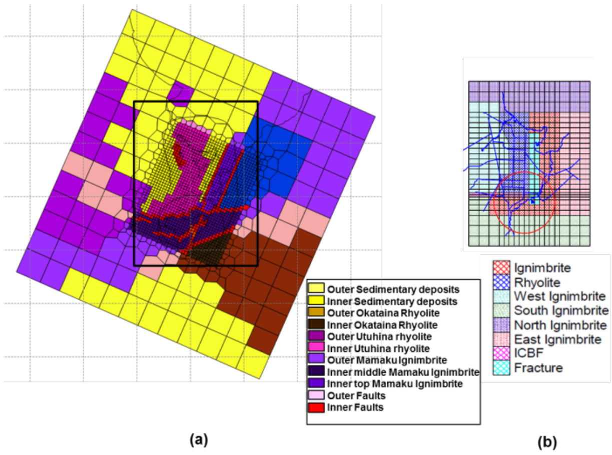

Figure 12: (a) UOA Model 4a and (b) IRL Model 2 geological settings at 100 masl.

5. BOUNDARY CONDITIONS

Top boundary: Atmospheric conditions are assigned at the top surface (1 bar, 15^0C). Below the lake surface, the pressure is set to the hydrostatic pressure corresponding to the depth of the lake assuming a water temperature of 10^0C. The bathymetry of the lake was retrieved from International Lake Environment Committee Foundation (ILEC). And the mean water level of 280 masl for Lake Rotorua was sourced from BoPRC (2013).

An annual rainfall of 1,000 mm/year and an infiltration rate of 10% are used. It is represented by cold water injected into the top of the model. Over the urbanized zone an infiltration rate of 8% is implemented in UOA Model 4a to account for paved areas and the existing drainage system.

Side boundaries: All the side boundaries are assumed to be closed; i.e. no heat or mass coming into or going out of the system. The side boundaries are located sufficiently far from the active system for this approximation to be valid.

Base boundary: Inflow of high enthalpy water up the inferred faults (Table 2) and a conductive flow of heat of 80 mW/m^2 are applied elsewhere. Chloride and CO_2 are injected into the system as percentages of the injected mass (Table 2).

Table 2: Deep inflows at the bottom layer of the model for UOA Model 4a.

	UOA Model 4a (Bottom: 2000m)				IRL Model 2 (Bottom: 570m)	
Area	Mass t/day	T ^{0}C	Cl (%)	CO_2 (%)	Mass t/day	T^0C
Ngapuna Stream	18,790	270	0.13	2.50	17,300	220
Whakarewarewa	34,560	245	0.09	1.20	30,320	200
Kuirau Park	6,750	255	0.04	2.0	2.420	200

6. NATURAL STATE MODELLING (PRIOR TO 1950)

The natural state represents the unchanging state of the field before exploitation. To simulate such a state, the model is run until a steady state is reached. There is little field data from that time period with which to compare the model results. However a few parameters are known or have been approximated.

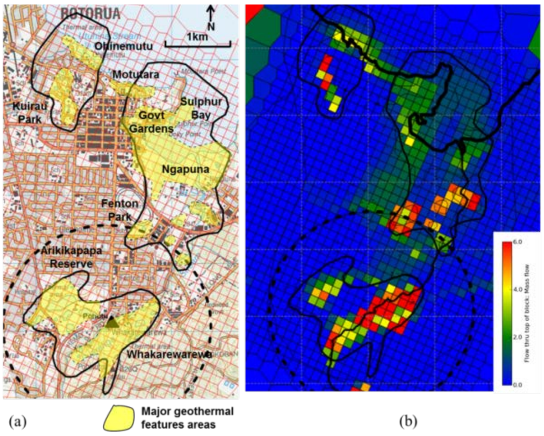

Figure 13: Natural State conditions for surface mass flow (kg/s): (a) Rotorua city and major surface features (from topomap.co.nz) and (b) UOA Model 4a.

Areas of surface activity in the model, as shown by mass flows (Figure 13), are located within known locations of surface discharging features. Areas such as Ngapuna / Puarenga stream, Whakarewarewa, Arikikapakapa, Kuirau Park and Ohinemutu are well represented in the model.

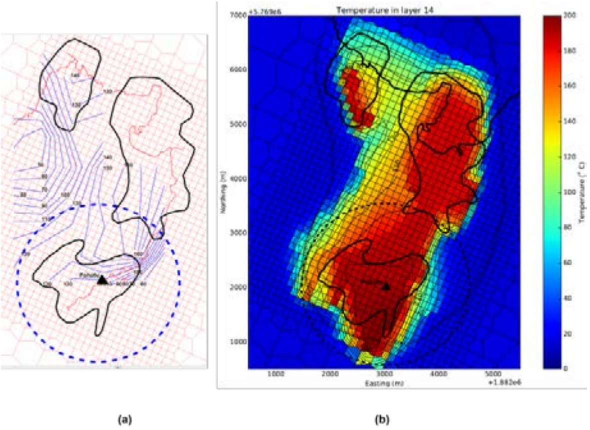

Figure 14: Temperature contours at 180masl. (a) Inferred by Wood (1992) and (b) UOA Model 4a.

Temperatures in UOA Model 4a exhibit a similar distribution to the inferred temperatures reaching 190°C at Whakarewarewa and in the eastern part of Ngapuna, and highlight three upflows: in the northeast (Whakarewarewa), along the Puarenga Stream in the East and at Kuirau Park (Figure 14).

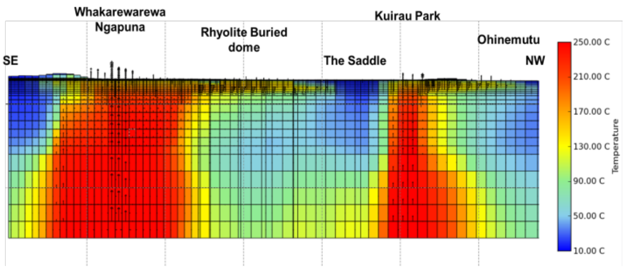

Figure 15: UOA Model 4a: NW-SE cross section of the temperature distribution (location in Figure 10)

Temperatures also highlight NW/W geothermal outflows across the Buried Dome and a shallow cold water inflow from the West into the Saddle area between Arikikapakapa and Kuirau Park (Figure 15).

7. PRODUCTION MODELLING (1950-2005)

The models were run for 36 years using the withdrawal pattern shown in Figure 16. Little information on the production distribution is available and therefore production and injection were applied uniformly across the known production and injection wells.

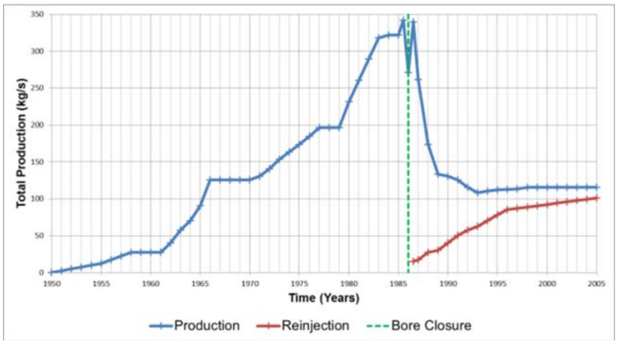

Figure 16: Rotorua production history (from Gordon et al., (2005) as cited in Ratouis *et al*., (2014)).

7.1. Pre Wellbore Closure (1950-1986)

Similarly little quantitative data describing the impact of the reservoir depletion is available as the Monitoring Programme began in only the 1980's when the reservoir pressure had already significantly declined.

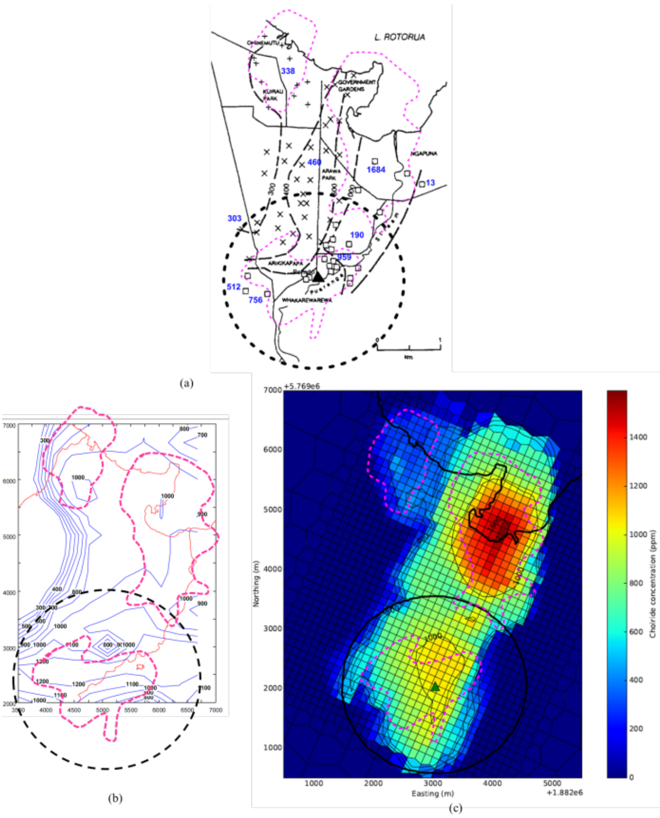

Figure 17: Chloride concentration (mg/kg) in 1984-83. (a) Contours from Stewart *et al*., (1992) (discrete values are provided in blue), (b) IRL Model 2 at 180 masl and (c) UOA Model 4a at 180 masl.

The chloride distribution in geothermal bores after 34 years of production was plotted against data gathered by Stewart *et al*. (1992) (Figure 17).

The overall representation of chloride levels within the reservoir is close to measured data (Figure 17). The model replicates the near N-S trend of the high chloride zone, an increase in concentration around Kuirau Park and the extent of the zone (>300mg/kg) affected by geothermal fluid (Figure 17).

The model matches well the extreme values and some discrete points of the field data (blue in Figure 17, Table 3). The highest chloride (1550 mg/kg) and temperature in Ngapuna is consistent with the characterization of the zone as the main upflow for the RGF. High chloride zones are also located near Whakarewarewa (1000 mg/kg) and underneath Kuirau Park (350mg/kg). The decrease in chloride content within the Rhyolite Dome correlates with the increasing degree of dilution of deep geothermal water with a low-temperature, low-chloride fluid (Glover and Mroczek, 1998).

UOA Model 4a gives a closer match to the chloride data than IRL Model 2 (Table 3).

Table 3: Comparison of measured chloride concentration.

Chloride concentration (mg/kg)	Measured	UOA Model 4a	IRL Model 2
Ngapuna	1683	1550	1000
	13	41	>1000
Whakarewarewa	190	430	1200
	959	1000	>1200
	756	698	1130
	512	531	1000
Rhyolite dome	303	306	550
	460	740	900
Kuirau Park	338	350	900

However the high chloride zone is too broad in the vicinity of Whakarewarewa, the Rhyolite Dome and Government Gardens as highlighted by the 400 and 500 mg/kg contours in Figure 17. The model underestimates the dilution of the geothermal fluid as it flow into the rhyolite dome or overestimate the amount of chloride bearing fluid in the outflow.

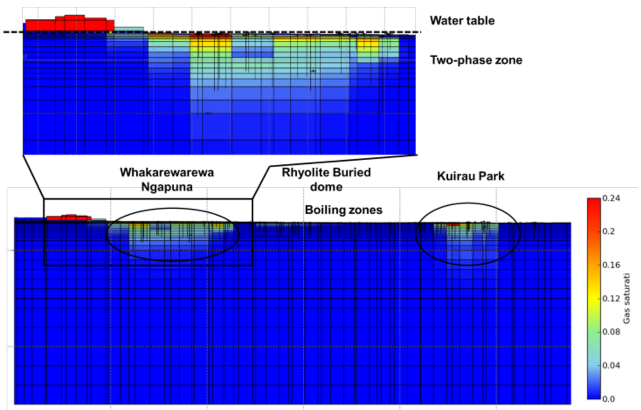

Figure 18: NW-SW Cross section of gas saturation in UOA Model 4a.

Figure 18 indicates that boiling occurs in the shallow parts of the reservoir beneath the three upflow zones. As a consequence, chloride concentration increases (Figure 19) and CO2 is liberated in the gas phase, highlighted in Figure 20 by a decrease in the mass fraction of CO2 in the liquid.

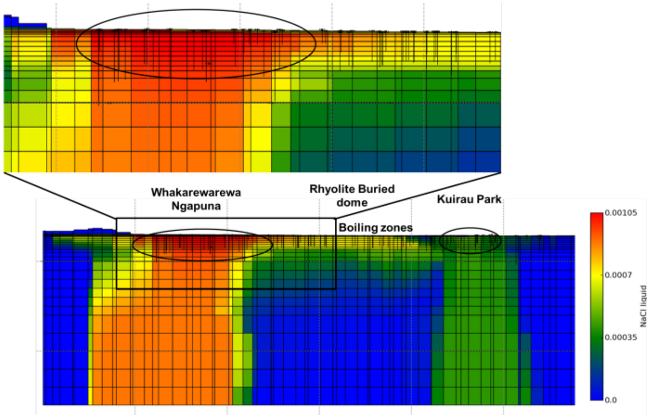

Figure 19: NW-SE Cross section of chloride distribution in UOA Model 4a.

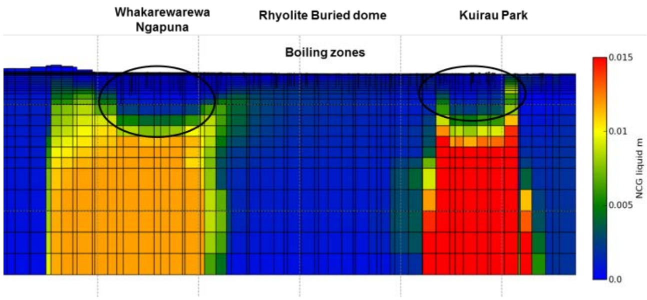

Figure 20: NW-SE Cross section of CO2 liquid mass fraction in UOA Model 4a.

It was necessary to have three independent upflows with different chloride and CO_2 percentages assigned to match the field data (Table 2). The model does not reach a sufficient depth (and does not include the subsequent mixing necessary) to represent accurately a possible single source of parent water.

7.2. Post wellbore Closure (1986-2005)

To model the impact of the 1986 Bore Closure Programme all wells within the exclusion zone were shut; injection wells were added and the model was run for another 19 years using production and injection estimates shown in Figure 16.

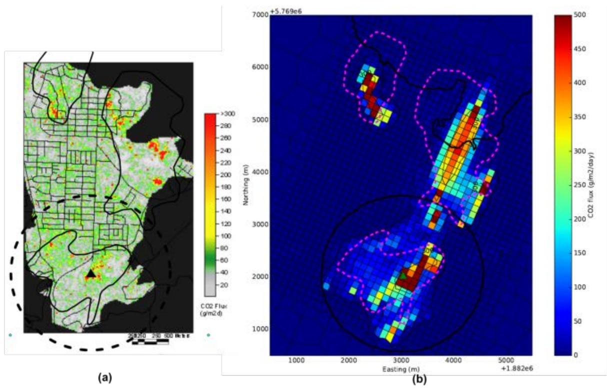

Figure 21: Surface CO2 flux in 2003. (a) Werner and Cardellini (2005) and (b) UOA Model 4a.

The model results retrieved after 53 years of simulation (2003) are consistent with Measured CO_2 emission data provided by Werner and Cardellini (2005) (Figure 21). High fluxes (>300g/day/m^2) were found above the upflow zones Ngapuna, Whakarewarewa, Kuirau Park (Figure 21). However the current model failed to reproduce high CO_2 fluxes at Government Gardens.

From 1950 to 1984 chloride content in the model increased in upflow areas (Ngapuna, Whakarewarewa and Kuirau Park) as well as in Government Gardens (red in Figure 22 a). West of Whakarewarewa, East of Ngapuna and at the western boundary of the Rhyolite Dome the chloride concentration decreased during the same period (blue in Figure 22 a).

Between 1984 and 1990, the areas identified above exhibited opposite trends: a decrease of chloride content in upflow zones and Government Gardens and an increase of chloride at the periphery of the field (Figure 22 b).

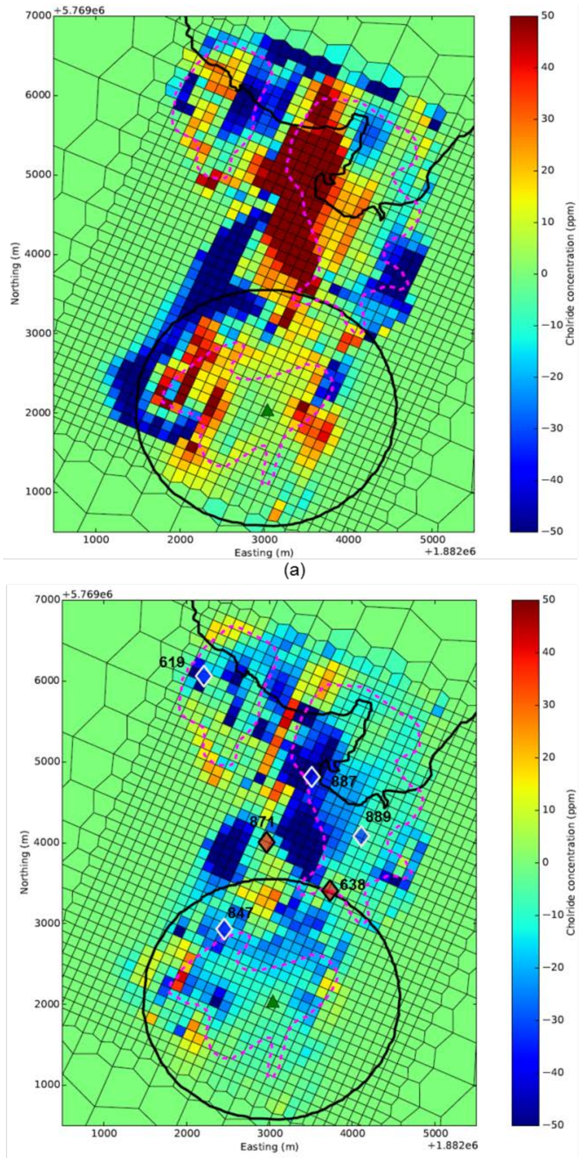

Figure 22: Chloride content changes. (a) From 1950 to 1984 and (b) From 1984 to 1990. Red respectively blue diamonds represent wells with chloride content increase respectively decrease.

Chloride values measured (Stewart *et al.*, 1992) also highlight two opposite trends in similar areas of the field. Chloride values in wells 619, 847, 887 and 889 showed a general decrease in concentration between the 1983-84 and 1989-90 campaigns; and wells 638 and 871 located in the vicinity of the Saddle displayed an increase in chloride content (color-coded diamonds in Figure 22 b).

The following interpretation is offered for the decreasing trend of chloride observed in blocks close to main upflow zones (Figure 23). Increasing production from the geothermal bores induced a reservoir pressure reduction which in turn increased boiling and the chloride content together with a general decrease in temperature (cooling from boiling and/or from a cold water intrusion from the side of the model. The phenomenon is closely related to production. As reinjection starts the situation is reversed.

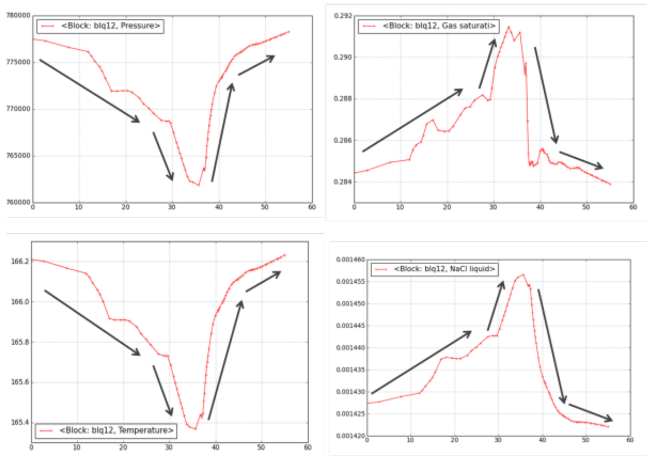

Figure 23: Pressure, temperature, gas saturation and chloride content history plots of a block in Ngapuna.

A second type of behaviour was observed for blocks located at a distance from the upflow zones (in the Rhyolite dome outflow) and is interpreted as follows. As production began, the pressure reduces which induces an increase in the flow of high chloride bearing fluid from the upflow zones. As the pressure drops below a threshold value cold recharge from the side becomes the dominant flow. As reinjection starts, the pressure increases, and high chloride bearing fluid returns slowly to this region.

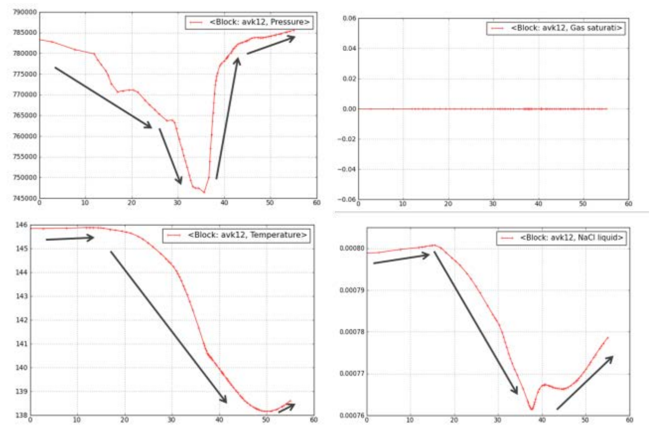

Figure 24: Pressure, temperature, gas saturation and chloride content history plots in the Rhyolite Dome.

8. DISCUSSION AND CONCLUSIONS

The chloride and CO_2 flow within the Rotorua Geothermal Field has been successfully modelled using EWASG module in TOUGH2. It provides helpful insights of the flow pattern of the Rotorua reservoir and its response to the production and reinjection currently in place. Chemical modelling offers an additional tool for studying and understanding the behavior of the surface features that are extremely important to Rotorua and New Zealand in general.

Numerical modelling is a useful tool for an integrated and sustainable management of the Rotorua geothermal resource with the following aims: enhancement and allocation of the resource, managing and controlling adverse effects on the field, and protecting surface features.

This modelling work could be a first step to a fully integrated geochemical model using TOUGHREACT (Xu *et al.*, 2004) to simulate bicarbonates and tritium levels.

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