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3-D Geoscience Modelling: Why Is It essential? A Case Study of the Rotorua Geothermal Field in New Zealand

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ABSTRACT

The Rotorua Geothermal Field, New Zealand, is renowned for its spectacular natural features and cultural heritage around geothermal uses by local Māori people. Rotorua City is built on top of the resource. It is a thriving city and a key destination for "geothermal tourism". To optimize the use of the resource without compromising safety nor affecting its natural expressions, the local authorities have supported many geoscientific studies in that area to understand and monitor the dynamics of the field.

Building 3-D geoscience models that integrate multidisciplinary geological, geochemical, geophysical and reservoir datasets in one model is essential to better understand geothermal resources and has become standard practice in the New Zealand geothermal industry, including for the Rotorua Geothermal Field. A 3-D geoscientific model has been developed starting with a geological model as its foundation that combines surface and subsurface geological and structural data/interpretation. The surface features and bores locations, temperature and chemical signatures has been added to the model as well as surface/subsurface geophysical survey (seismic, magnetotellurics, gravity, and thermal infra-red). The current phase of model development focusses on rock property modelling within key reservoir units to identify with more details the exact fluid flow pathways using the surface features temperature and chemical signature and aims to refine the current conceptual understanding of the field in a 3-D environment. This data-driven 3-D conceptual representation of the field aims to better inform numerical models that simulate the reservoir behaviour.

In this paper, we present the impact a comprehensive 3-D geoscience model is having on the development of our understanding of the Rotorua geothermal resource and its applications for sustainable field management.

1. INTRODUCTION

The Rotorua Geothermal Field is located in the Taupo Volcanic Zone (TVZ) of New Zealand (Figure 1). It is renowned for its spectacular natural features and cultural heritage around geothermal uses by local Māori people. Rotorua City is a thriving city built on top of the geothermal resource which has become a key destination for "geothermal tourism". Many surface features are present and include hot springs, geysers, mud pools, and steaming ground, widespread in several thermal areas across the field (Figure 1).

Surfacing geothermal waters have historically been used by Māori for their curative properties, bathing, cooking and heating (Neilson et al., 2010). Initially the use of the geothermal resource in Rotorua was relatively low impact, but an increasing demand for energy in the 1950s led to extraction on a larger scale, with over 1000 geothermal wells by the 1970s. This extraction was effectively uncontrolled, and most geothermal water was discharged to waste (Doorman and Barber, 2017). To date, while there is no electricity generation in Rotorua, nor any large industrial process heat use, the resource is used for bathing, wellness, space and water heating for residential and commercial properties (Doorman and Barber, 2017; Climo et al., 2020).

Over-exploitation of the resources by the mid-1980s, led to decline in the natural hydrothermal activity, pressure drop in the reservoir and increased hydrothermal eruptions (Scott and Cody, 2000). The situation raised the government awareness of the safety risks and cultural and commercial consequences of the decline and were addressed by a change of management policy (Allis and Lumb, 1992). The New Zealand government, in consultation with a scientific task force that directed a large scientific investigation campaign of the field between 1980 and 1990, instigated a bore closure programme. An exclusion zone allowing no extraction was created for a 1.5 km area around the geyser field of Whakarewarewa, and constraints on net heat and fluid withdrawal on the remainder of the resource. Production was reduced by ~60% to allow for field recovery (Scott et al., 2016).

Under the New Zealand Resource Management Act (1991), the Rotorua Geothermal Field is managed by the Bay of Plenty Regional Council (BOPRC). The Rotorua Geothermal Regional Plan (RGRP) was developed with the purpose to promote the integrated and sustainable management of the Rotorua geothermal resource (Rotorua Geothermal Regional Plan, 1999). Aims of the RGRP include enhancement and allocation of the resource, managing and controlling adverse effects on the field and protecting surface features (Doorman and Barber, 2017). A review of the management plan is in progress to reassess the appropriateness of existing limits on heat and fluid withdrawal (Doorman and Barber, 2017). To support its decision-making process, BOPRC is seeking technical inputs to build an understanding of the resource available for allocation, current use, and system responses to inform planning decisions. To that effect, BOPRC supports many geoscientific studies to better understand and monitor the dynamics of the field.

In 2014, BOPRC instigated the development of a geological model of the Rotorua Geothermal Field (Alcaraz, 2014; Alcaraz and Barber, 2015) to provide a structural framework for geoscientific data integration. Over the following years, the model was further developed and is holding inputs from geophysics, hydrology and geochemistry, heat flow survey, thermal infrared survey, bores and natural feature monitoring and reservoir data.

Most recently, BOPRC's focus is on improving the reliability of direct geothermal usage data as described in Climo et al. (2020). Actual monitoring of energy usage from the 130 consented holders (Doorman and Barber, 2017) is another dataset that will be used in the reservoir simulation models to more accurately predict and model the effects of this use and review future allocations.

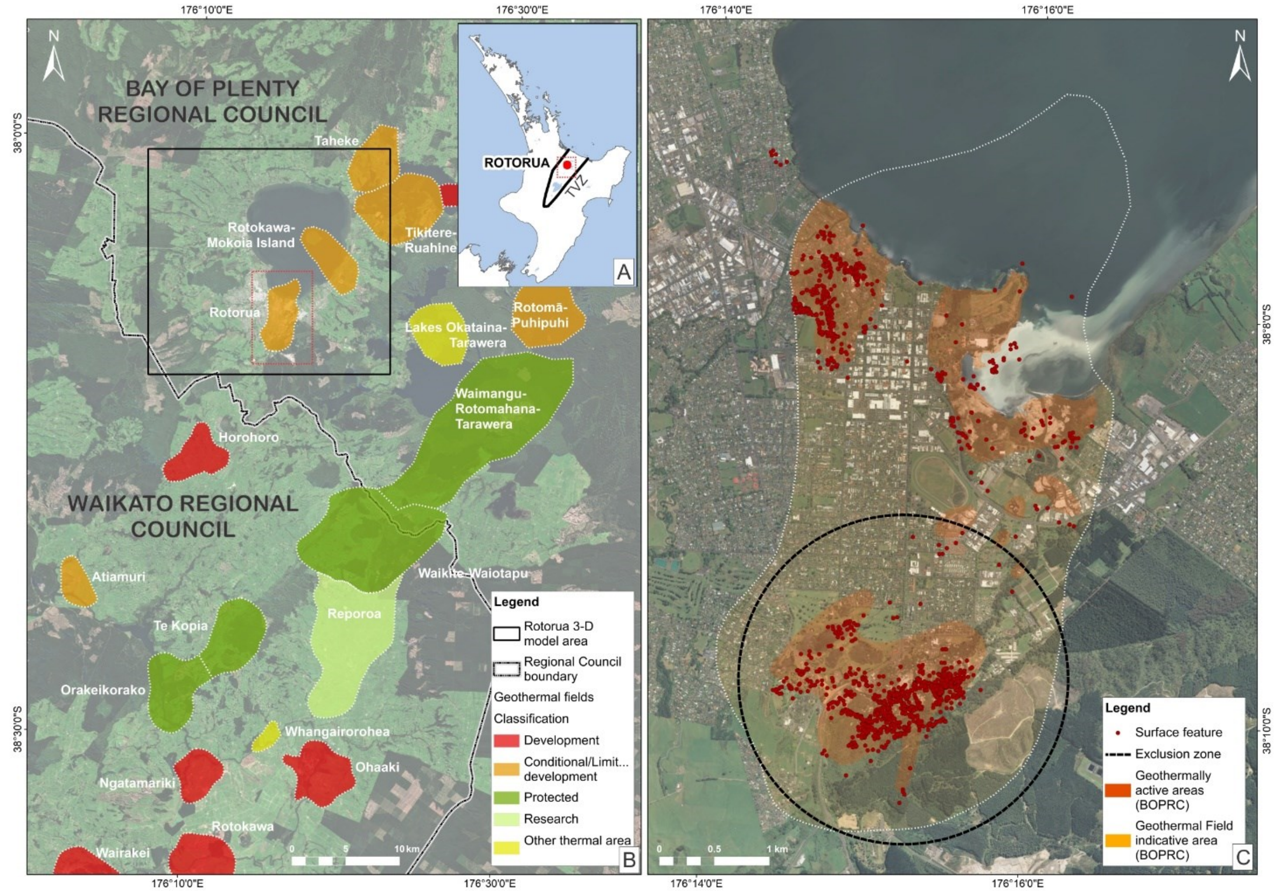

Figure 1: The Rotorua Geothermal Field. A: Location of Rotorua in New Zealand. B: Location of the Rotorua Geothermal Field in relation to other geothermal fields in the Taupo Volcanic Zone (TVZ). C: Rotorua City is built on the geothermal field, with concentration of surfacthermal features in the geothermally active areas.

2. THE ROTORUA GEOLOGICAL MODEL

The purpose of the 3-D geological model is to gain a better understanding of the geological framework of the area, including stratigraphic correlations and structural setting. This involved the gathering and compiling of geoscientific datasets available for the area including subsurface data from >1300 shallow wells, surface geological maps, seismic profiles, gravity maps and magnetolleric (MT) profiles and models (Alcaraz, 2014). These datasets were used to build a 3-D geological model that provides a platform for data integration to illustrate and model the geothermal reservoir behaviour and response to utilisation.

2.1 Geological setting

The Rotorua Geothermal Field lies within the southern part of the Rotorua caldera. Based on shallow electrical resistivity maps, the Rotorua Geothermal Field covers an area of about 18 km^2, as defined within the 30 Ωm resistivity contour at surface, but may extend to 20 – 28 km^2 at 500 m depth (Bibby et al., 1992).

The most significant event in the geological history of Rotorua is a caldera collapse episode associated with the eruption of the Mamaku Ignimbrite ~ 240,000 years ago. Pre-caldera domes and ignimbrites surround the area; however, the exact nature, distribution and geometry of underlying formations is unknown. The Mamaku Ignimbrite outcrops beyond the edges of the Rotorua caldera, extending farthest towards the north-west. Within the collapsed area a lake formed along with rhyolite dome complexes. The depression is infilled by a sedimentary sequence of mixed lacustrine, fluvial and volcanic deposits. The level of the lake varied in time as younger eruptions from the near-by Okataina Volcanic Centre dammed the outlet of Lake Rotorua, resulting in the formation of several lake terraces within the caldera inner slopes, well beyond the shores of the modern Lake Rotorua. Younger pyroclastic deposits from the Okataina Volcanic Centre surface east of the caldera.

2.2 Geological data

The surface geology and structures of the Rotorua area have been described by many authors (e.g. Healy et al., 1964; Lloyd, 1975; Wood, 1992; Milner, 2002; Jongens and Dellow, 2003 ; Leonard et al., 2010; Ashwell et al., 2013). While the surface outlines of the different units are mostly consistent between these authors, the structural interpretations vary due to the structures within the caldera being buried. Intra-caldera faults postulated by Lloyd (1975), Wood (1984; 1992), Milner (2002) and Ashwell et al. (2013) have been considered to build the structural network of the model, based on evidence from borehole data, thermal feature lineaments and possible inherited basement structures.

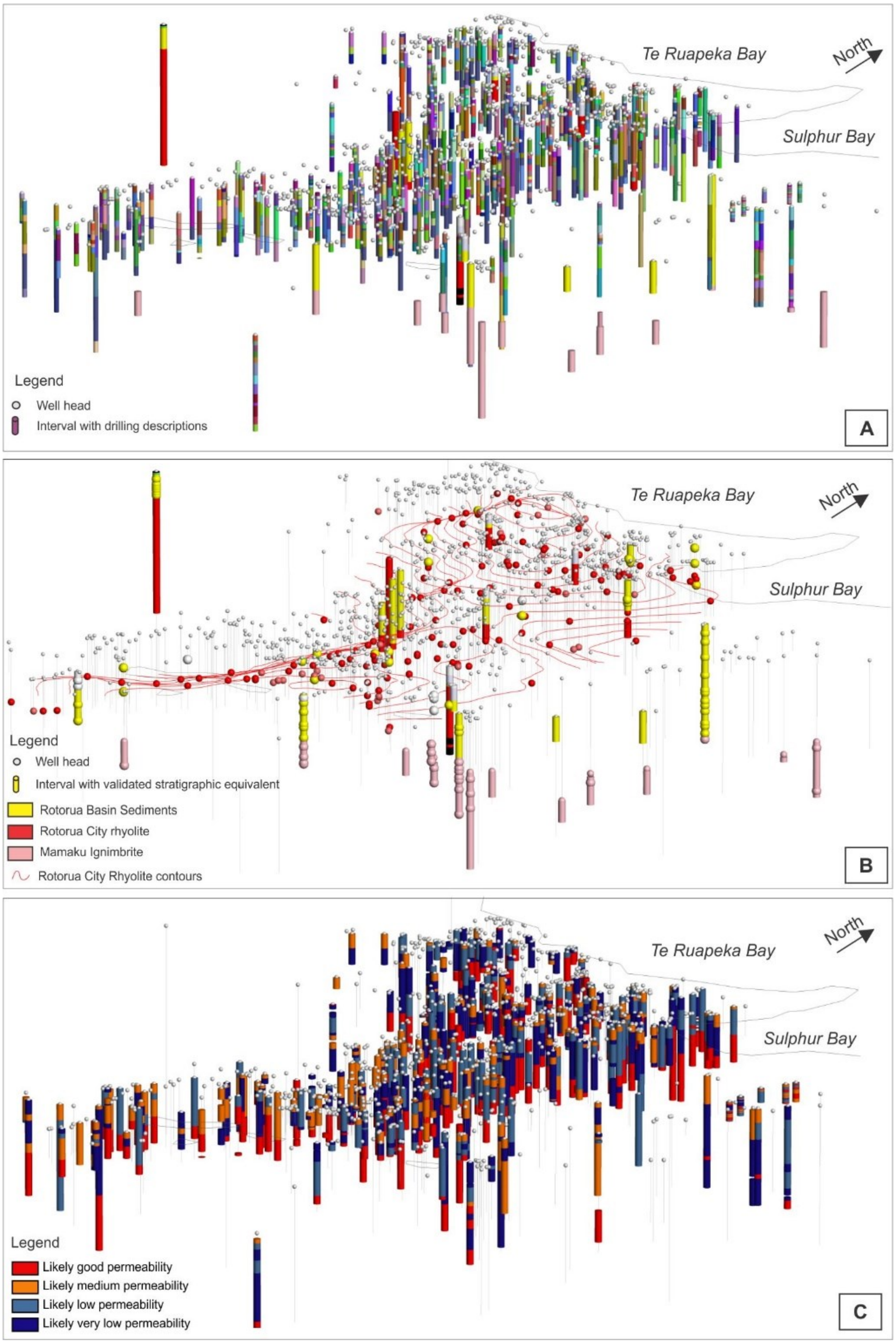

Figure 2: A: 3-D view of the driller logs available in the Rotorua City area. B: Reliable geological data after validation. C: Classification of the well data into permeability groups (Alcaraz and Orozco, 2018).

The geology at depth within the caldera is poorly constrained, even though more than a thousand drillholes have been drilled in and near Rotorua City since the 1920s (Figure 2). Most wells do not exceed a couple hundred metres drilled depth and geological data was not recorded systematically before 1978. Some logs have been described from drill cuttings by geologists, but most available data are driller logs (Figure 2A) with descriptions that are subject to the limitations of varying interpretations (Crafar, 1974; Wood, 1984; Wood, 1992). As part of the data validation process (Alcaraz and Orozco, 2018), the driller logs were compared with reliable interpretation from geologists familiar with the Rotorua geology. It clearly showed that these descriptions are often inconsistent and cannot be used systematically to define key lithologies and establish stratigraphic correlations (Alcaraz and Barber, 2015). While reliable stratigraphic information was limited (Figure 2B), useful information on the likely permeability of the rock could be extracted from the lithological descriptions (Figure 2C).

The geological unit that is well constrained from drilling data is the Rotorua City Rhyolite, one of the post-caldera rhyolite complexes. This unit has been intersected by > 100 drillholes (Figure 2B), shaping two domes that form a N-S elongated ridge separated by a saddle. These domes are mostly buried beneath sediments and breccias. The base of the domes has never been intersected. While unproven, it is most likely that they lie on the Mamaku Ignimbrite that infilled the entire caldera depression at the time of deposition.

The upper units of the Mamaku Ignimbrite have been intersected by several wells south-east of the city though none reached the base of the formation. A minimum thickness of c. 200 m is proven from borehole data (Wood, 1992).

The ignimbrite and rhyolite domes are buried beneath the Rotorua Basin Sediments. The upper few tens of metres of the sedimentary sequence generally contain primary and reworked pumiceous tephra of usually high porosity. The lower sedimentary sequence is made up of mostly impermeable muddy sands and silts that act as an aquitard for the geothermal aquifer (Wood, 1984). The sediment types vary considerably across the area based on localised depositional environment and volcanic activity. Based on the overall poor quality of geological data available and high vertical and horizontal variability of these sediments, it was believed impossible to establish a type sedimentary sequence that could be spatially correlated across the field (Wood, 1984; Wood, 1992). Considered as a whole, their maximum known thickness from borehole data is 235 m.

In addition to the bores drilled in the Rotorua City area, wells located on the outskirt of the caldera rim provided useful constraints on the depth and/or thickness of the Mamaku Ignimbrite. These include the Te Akau wells (Kaituna River Hydro Schemes), the Kaharoa well and the Tikitere Geothermal Field wells to the north, the Dillon drillhole to the south, and numerous groundwater bores drilled along the Mamaku Plateau to the west and reported in White et al. (2007).

Stratigraphic units older than the Mamaku Ignimbrite have not been drilled through and their distribution and thickness are inferred from the regional distribution and geological knowledge of the region.

2.3 Geophysical data

Geophysical studies considered in this project include seismic, gravity and magneto-telluric (MT) surveys, which provide complementary information on the likely subsurface geology and structures.

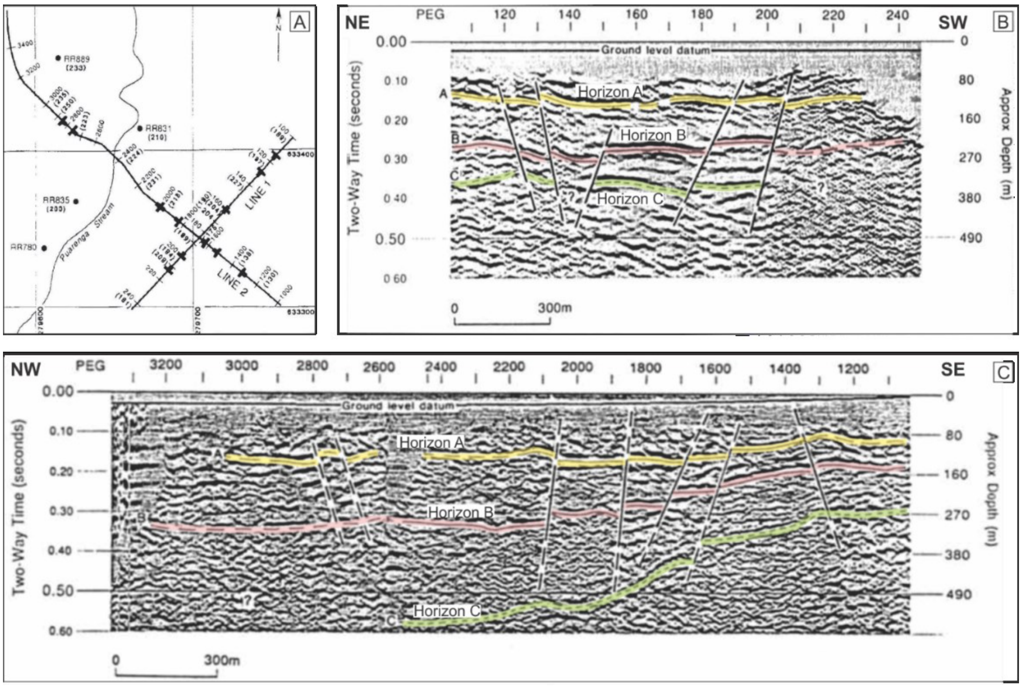

Figure 3: Seismic profiles and interpretation from Lamarche (1992). A: Location map of the seismic profile and pegs, showing the estimated depth to the top of the Mamaku Ignimbrite. B: SW-NE seismic profile along line 1. C: NW-SE seismic profile along line 2. Horizon A (yellow): lacustrine sediments. Horizon B (pink): top of the Mamaku Ignimbrite. Horizon C (green): possible contact between Mamaku Ignimbrite and Pokai Formation.

Seismic data

Lamarche (1992) presents the results of a seismic reflection survey done in the south-eastern part of the Rotorua Geothermal Field (Figure 3). Interpreted geological structures are represented along two profiles, including the correlation of seismic reflectors to known stratigraphic layers from nearby wells (Wood, 1992). Horizon A corresponds to lacustrine sediments of the Rotorua Basin Sediments unit, Horizon B is identified as the top surface of the Mamaku Ignimbrite, and Horizon C, though discontinuous, is interpreted to be the contact between the Mamaku Ignimbrite and the underlying Pokai Formation. No boreholes are deep enough to confirm the latest. Discontinuities and offsets in the seismic profiles have been identified as a series of at least four normal faults coinciding with the assumed location of the Inner Caldera Boundary Fault postulated by Wood (1984; 1992), with vertical displacements on any one fault no greater than 30 m. Down-faulting and dip of the surface contributes to the elevation differences of the top of the Mamaku Ignimbrite from southeast to northwest and implies a thickening of the formation towards the northwest, in agreement with observations from Wood (1992).

Gravity data

The Rotorua caldera presents a complex and atypical gravity signature compared to other rhyolitic calderas, which usually have a circular negative gravity anomaly (Macdonald, 1974). Hunt (1992) identifies a gravity low west of Lake Rotorua with three minima. The Pukerora anomaly (Figure 4) is a gravity high coincident with the buried Rotorua Rhyolite domes beneath Rotorua City, and provides additional insights on the lobes geometry where borehole data is not available. On the other hand, the Linton Park gravity low is inferred to be related to a considerable thickness (> 1 km) of low-density material including sediments (Hunt, 1992), and possibly Mamaku Ignimbrite (Rogan, 1982). It also indicates that there is no rhyolite at depth in this area (Hunt, 1992).

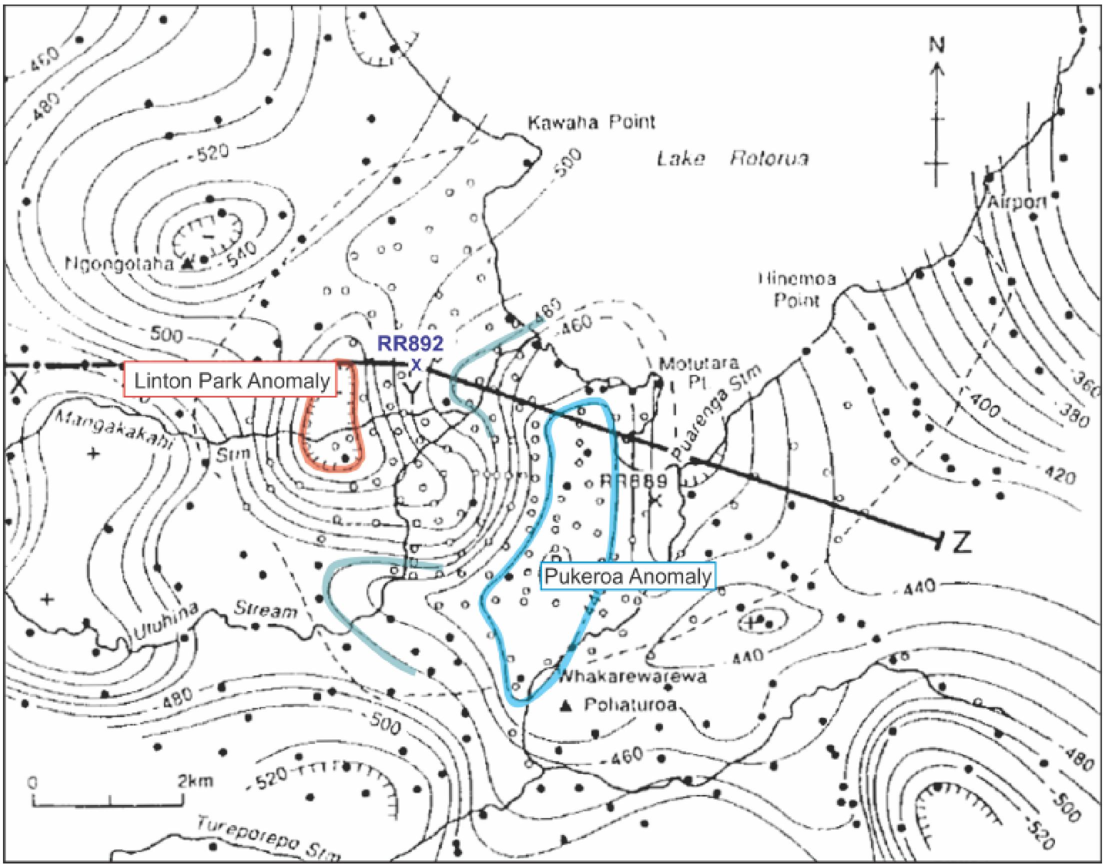

Figure 4: Residual gravity anomaly map of Rotorua City area from Hunt (1992)Contour interval is 10 µN/kg. Anomalies discussed in the text are highlighted.

MT data

Most recently, BOPRC commissioned an MT survey to provide insights on the extent of the deep-resistivity structure of the geothermal system. Results of the survey have been presented as 2D and 3D inversion models (Caldwell et al., 2014; Heise et al., 2016). These outputs are used in the Rotorua 3-D geoscience model to constrain the location of key geological/structural features as identified by these authors (Figure 5). Findings show that the top of the conductive zone is situated directly beneath the area of greatest surface heat and gas discharge (Heise et al., 2016). The shallow low resistivity layer beneath the Rotorua Geothermal Field is interpreted as being the clay cap overlying the hotter parts of the geothermal system. The deep resistor northwest of Rotorua is interpreted as representing the basement rocks, hence providing indications on the likely location of the caldera floor as well as the location of the caldera margin in area of high resistivity contrasts (Caldwell et al., 2014).

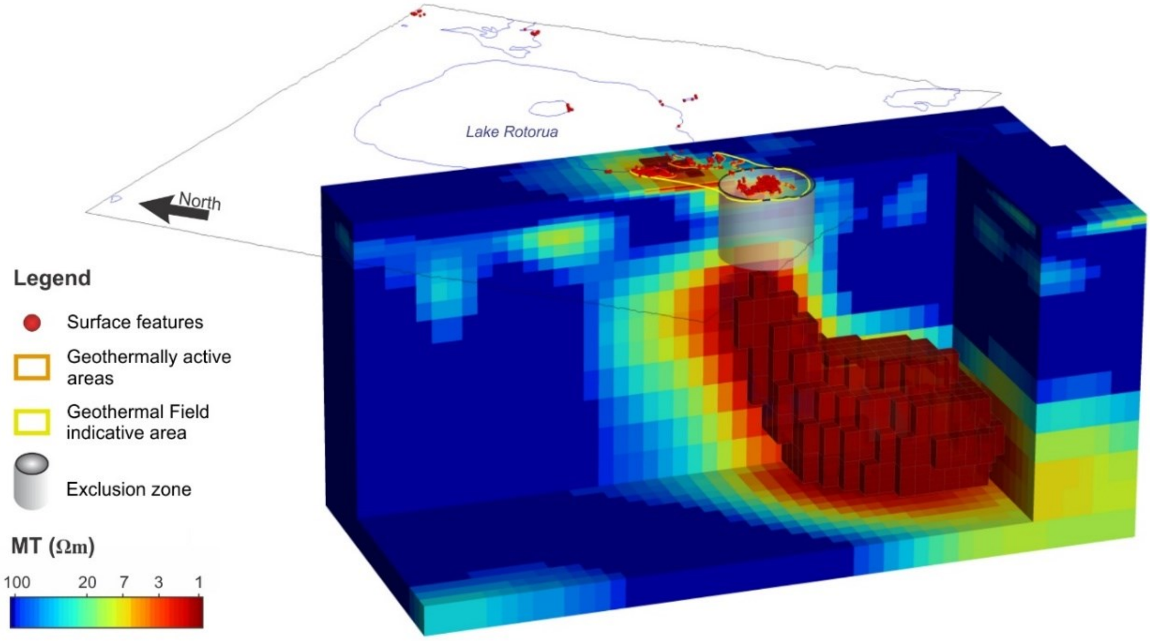

Figure 5: Visualisation of the 3-D MT model in the Rotorua geoscience model (the MT model is presented in Heise et al., 2016).

2.4 The geological framework model

Geological data in the Rotorua are is limited by the shallow depth and restricted geographical coverage of the drillholes. Geophysical data was used to provide needed constraints on the likely architecture of the units at depth, as illustrated in Figure 6.

The model includes 10 faults that represent a simplified but realistic structural network. The Rotorua caldera is the most significant feature in the area. Its topographic margin is well-defined on all sides by fault scarps, except to the north-west where the Mamaku Plateau is gently dipping towards Lake Rotorua, without any obvious structural offset marking the caldera edge. The caldera outline from Leonard et al. (2010) was modelled as a sub-vertical structure. Other faults include the Ngakuru Fault Opawhero Fault, Whakapoungakau Fault and Horohoro Fault (Leonard et al., 2010). They represent the westernmost faults of the Taupo Fault Belt in this area and both dip to the south-east. To the north-east is the Tikitere Graben. Faults within the caldera are the Pohaturoa, Whakarewarewa and Puarenga faults from Lloyd (1975), and the Inner Caldera Boundary Fault (ICBF) from Wood (1984). The ICBF has been confirmed as a fault zone including at least 4 normal faults (Lamarche, 1992).

In the model, the basement depth within the caldera is controlled by the Caldwell et al. (2014) interpretation of the possible caldera floor from the MT signature west of Rotorua City. Above the basement, an undifferentiated Whakamaru Group and other deep ignimbrites of unknown characteristics and extents has been created. These ignimbrites may include the Chimp Formation and Matahina Formation but likely contain other local or regional deposits. Above these units comes the Pokai Ignimbrite, which has been mapped at surface south of the caldera rim, in combination with the Pokopoko Formation that was intersected in wells to the north and north-east of the model, providing constraints on the depth of the formation in this area. Pre-caldera rhyolitic domes outcrop on the edges of the Rotorua caldera and have been modelled solely based on their surface extent and dome-like geometry at depth.

The Mamaku Plateau Formation, also referred to as the Mamaku Ignimbrite, is one of the most widely distributed ignimbrites of the TVZ, associated with the collapse of the Rotorua caldera dated at c. 240 ka (Gravley et al., 2007). The ignimbrite formed during a single eruptive episode and can be separated in a basal tephra sequence and a main ignimbrite sequence itself subdivided into a lower, middle and upper unit (Milner et al., 2003). Wood (1992) suggested that evidence is strong to support the locus of the Mamaku Ignimbrite eruption and maximum subsidence was located south within the caldera, centred on the low gravity anomaly from Rogan (1982) and Hunt (1992). The depth of the top of the Mamaku Ignimbrite is controlled by borehole data to the south-east of Rotorua City and validated using Lamarche (1992) seismic profiles. The thickness of the Mamaku Ignimbrite in the caldera is unknown though Larmarche suggested a depth of up to 279 m.

The post-caldera Rotorua rhyolites are well-constrained from surface data and drillhole data below Rotorua City. Uncertainty remains whether these surface rhyolites are part of a single rhyolitic body below drilled depths and, until further information comes to light, they are modelled as such. The Rotorua Basin Sediments are modelled from the combination of drilling data (as an undifferentiated sequence) and surface expressions.

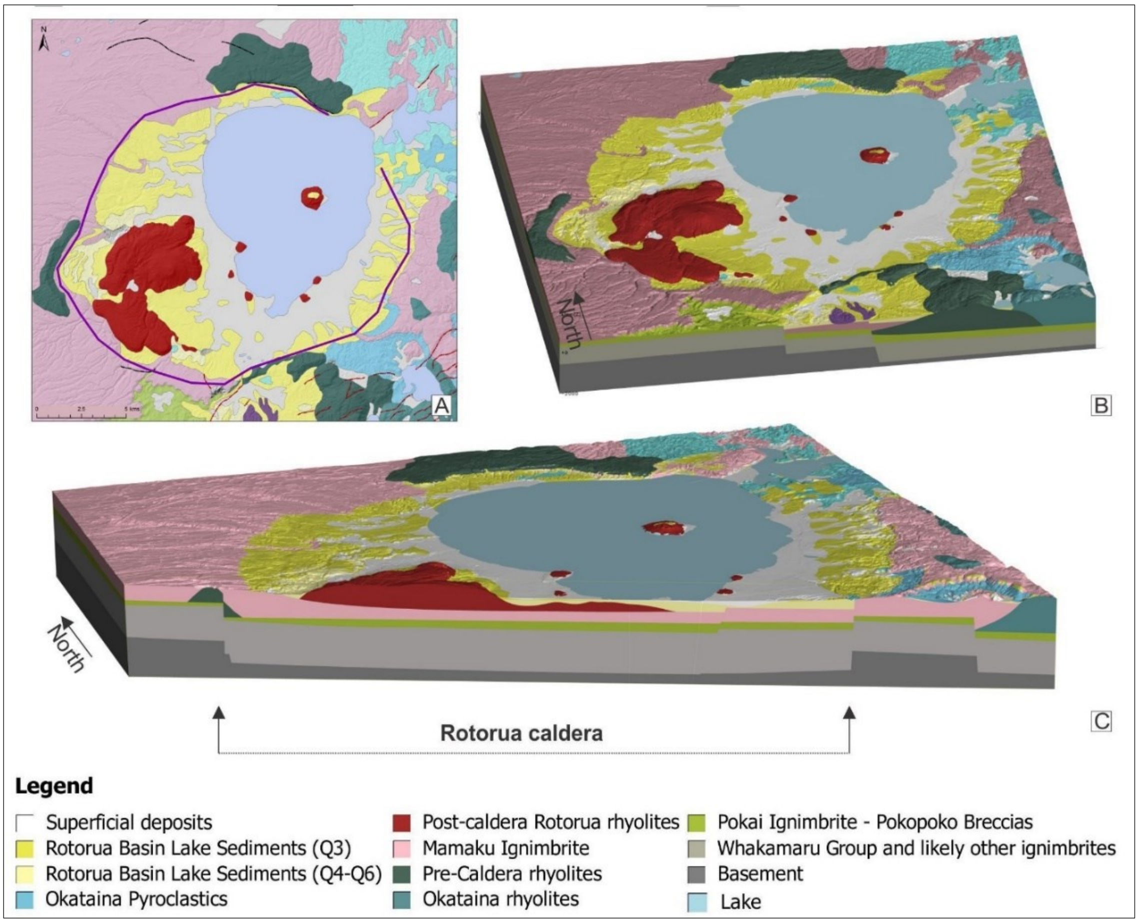

Figure 6: 3-D geological model of Rotorua. A. Original geological map at surface. B. 3-D view of the Model. C. WNW-ESE cut through the model.

3. HYDROLOGY AND DYNAMICS OF THE SYSTEM

BOPRC have maintained an uninterrupted monitoring program since 2008 for 40 selected geothermal surface features in the Rotorua field (Doorman and Barber, 2017). In addition, five geothermal bores and four shallow groundwater bores are also monitored for water and level and temperature profiles (Kissling, 2014).

3.1 Fluid chemistry

Based on the fluid chemistry two natural outflow areas are described at Rotorua (Giggenbach and Glover, 1992; Stewart et al., 1992), respectively at Ngapuna and Whakarewarewa in the east and south, and Kuirau Park - Ohinemutu in the North. These natural spring outflow areas are most likely to be connected and supplied by thermal fluids from depth. The geological structure of the area, the nature of the host rocks (e.g. rock type and chemistry) and field hydrology control the chemical character of the fluids as they approach the surface/near surface. Fluid that rises in the eastern part of the field discharges to surface features at Whakarewarewa and Ngapuna. Lateral flow to the west also takes place where shallow mixing of the fluids can occur prior to discharge. The input of deep thermal fluids and shallow mixing adds additional complexity to the outflow model for the Kuirau and Ohinemutu areas.

A summary of the chemical signatures of the thermal fluids in springs and sampled bores is described in Scott et al. (2016). As part of the current work, the chemical analyses from two sampling periods, respectively 1979-1990 and 2003-2009, have been revisited and recontoured for integration in the geoscience model (Figure 7).

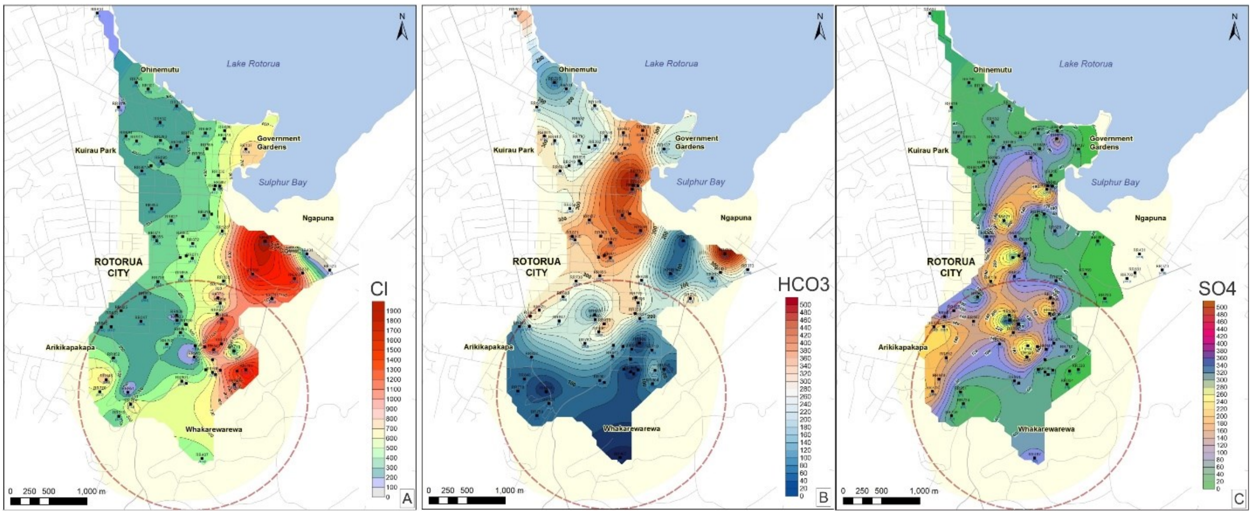

Figure 7: Chemistry contours for samples collected between 1982-1990. The warmest colours indicate higher concentrations in each map.A: Cl contours. B: HCO3 contours. C:SO4 contours.

A significant chemical characteristic of the Rotorua fluids is the decrease in Cl from Ngapuna (east) to Kuirau Park (west) (Figure 7A) and higher HCO3 concentrations between the two, centred broadly on the Government Gardens area (Figure 7B) and also seen in Kuirau Park (Stewart et al., 1992). The Cl is from the deeper sourced primary geothermal fluid while HCO3 arises from water–rock interaction at shallower depth. Condensation of steam and oxidation of H2S by groundwater results in elevated SO4 and acidic fluids at very shallow levels in many parts of the field (Scott et al., 2016; Figure 7C).

3.2 Temperature

Recent work included a re-evaluation of the down-hole temperature data available from 191 bores in the Rotorua area and inclusion in the 3-D geoscience model (Ratouis et al., 2017). Along with the down-hole temperatures from 191 bores (measured between 1953 and 2011), surface temperature contours (where available) and surface features temperatures were included to construct 3-D temperature contours representative of the field. Temperature contours at 180 masl in Figure 8 shows the main upflow zones at Whakarewarewa, Kuirau Park, and Ngapuna indicated by temperature maxima of between 180 and 200 °C.

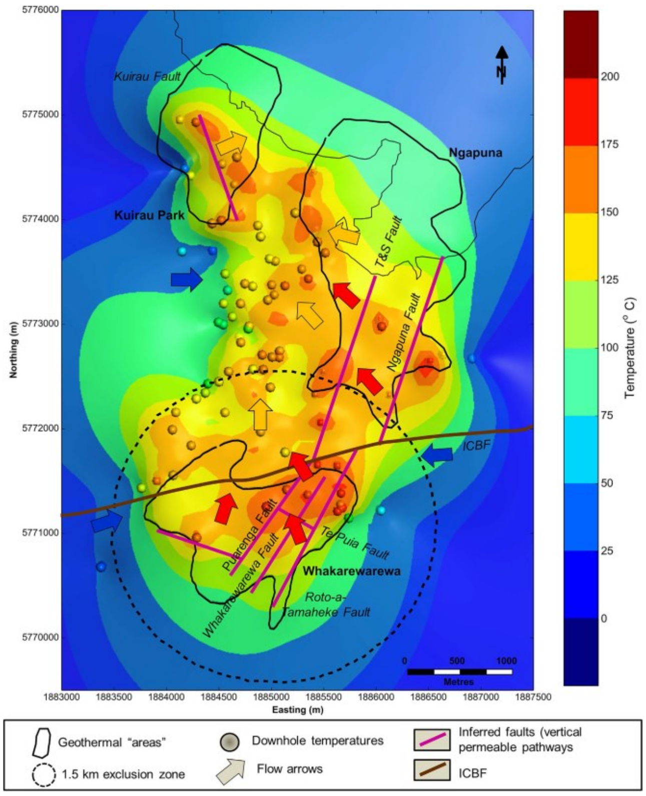

Figure 8: Temperature contour map at 180 masl (wells are indicated by the colored dots), including a simplified fault structure and mass flow (from Ratouis et al., 2017).

Lower temperatures and temperature inversions in geothermal bores across the Rotorua City Rhyolite highlight a lateral out-flow zone leading from the up-flow zones across the rhyolite domes towards the Lake and Government Gardens. The contours at 180 masl also show colder water around the Saddle between the Buried Domes to the west of the field and between the Whakarewarewa region and Ngapuna area to the East of the field (Ratouis et al., 2017).

The rhyolite and ignimbrite geothermal aquifers are overlaid by generally low permeability sediments of lacustrine origin. This cap is breached where temperature anomalies and geothermal surface features are evident (Whakarewarewa, along the Puarenga Stream, Government Garden, Ohinemutu, and Kuirau Park).

3.3 Thermal IR and Heat Flow

In order to properly calibrate the reservoir model, monitor surface heat-loss changes during production (use) for history-matching and assess the environmental effects of current uses, a comprehensive heat-flow survey of the field is underway (Seward et al., 2020). The program requires the monitoring and quantifying of heat loss from significant geothermal areas via remote sensing and ground-truthing. High-resolution air-borne infrared surveys (Reeves, 2014) and repeat ground measurements of shallow temperatures and calorimeter heat-fluxes are expected to achieve a long term improvement in the quantification of natural and induced changes in surface heat loss. Figure 9 is an illustration of the infrared image wrapped on the geological model, with location of surface features and contours of heat fluxes from ground-measurements.

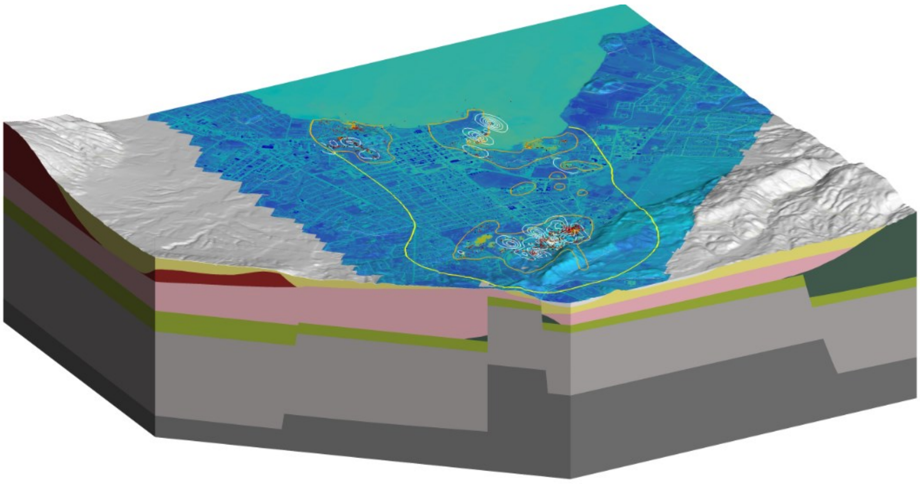

Figure 9: Thermal infrared image from Reeves (2014) wrapped on the geological model. Location of surface features and heat flux measurement sites (Seward et al., 2020) and contours are also shown.

3.4 Permeability indicators

As mentioned in section 2.2, the well data from driller logs is mostly unreliable for stratigraphic correlation, however, it contains a lot of qualitative descriptions that can be related to the rock type and/or size of the clasts, and bring some insights in the local permeability variations. The lithological description of each log was searched for keywords and reclassified (Figure 2C) to represent in 3-D the possible permeability variation within the rhyolite (Figure 10A) and sediments (Figure 10B) to better constrain the possible fluid flow within each unit. Furthermore, the distribution of impermeable sediments that act as an aquitard versus coarser sediments that may also hold useful resources would be a key to better refine the Rotorua Geothermal Field model.

The next step of this project will look at comparing the permeability variation model with the current hydrological model of the area based on the chemistry and temperature data, in particular, fluid flow pathways between the deep and shallow reservoirs and local areas of higher permeabilities that may host a resource within the Rotorua Basin sediments.

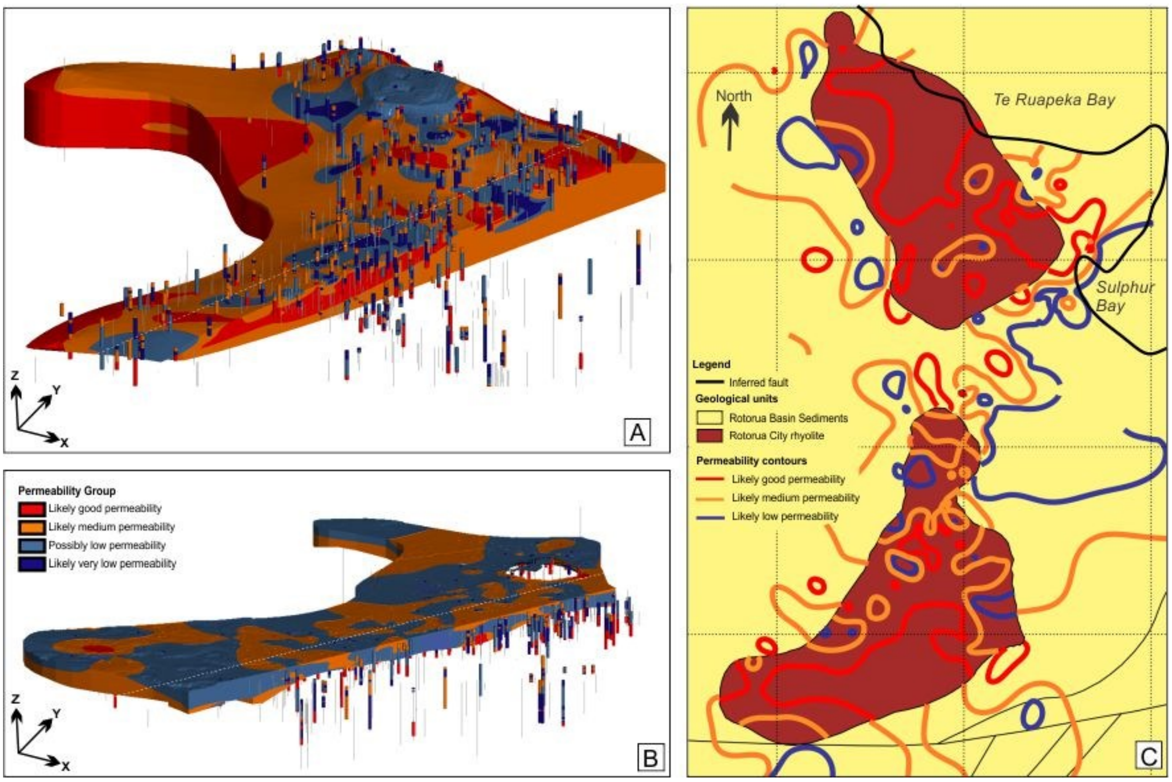

Figure 10: Permeability variation within the Rotorua Rhyolite domes (A) and within the undifferentiated Rotorua Basin Sediments (B). C: Likely permeability contours within the rhyolite, and within the sediments at 200m mRL.

4. RESERVOIR MODELLING

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 then, further models were developed to reproduce the behaviour of the field while in recovery and to give insight into possible future production scenarios (e.g. Burnell, 2005; Ratouis et al., 2016 and Ratouis et al., 2017).

A new update of the reservoir model commissioned by BOPRC is underway, supported by all scientific studies conducted in the last few years. The aim of the model is to provide detailed scenarios simulations to determine the likely response to increased production in various parts of the field to support the council in their policy reviews and geothermal resource management (Doorman and Barber, 2017). As we continue our study of the area and integrate new data (e.g. Figure 11), any changes to the rock type structure and refinement of fluid pathways will be conveyed to the reservoir model for update.

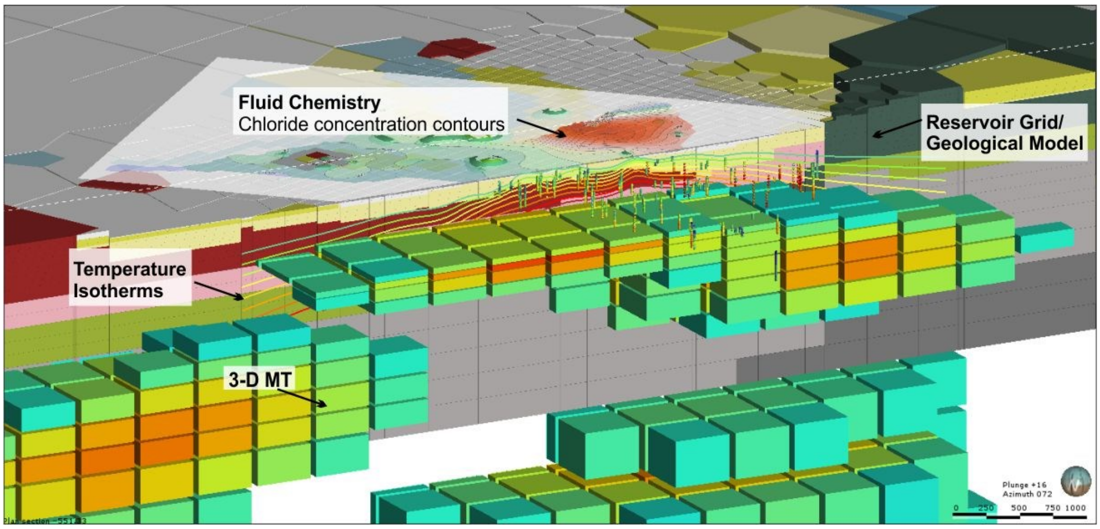

Figure 11: Example of data integration in the 3-D geoscience model of Rotorua. The Geological model is from Alcaraz (2014), the MT data from Heise et al. (2016), the geochemistry (this study from reviewed historic measurements) and the temperature and reservoir grid from Ratouis et al. (2016 and 2017).

5. SUMMARY

The Rotorua Geothermal Regional Plan prioritises surface feature protection over extractive uses by limiting net loss of geothermal fluid to the system, and restricting use close to Whakarewarewa geysers. This management approach has been effective and the recovery of the system is well documented. The plan is now due for a review and any change (or lack of change) to the policies needs to be supported by strong technical and scientific evidences. The review provides an opportunity to carefully consider opportunities to improve efficient use of the valuable resource.

BOPRC provides strong support and incentive for under-pinning research of the Rotorua Geothermal Field. A strong model of the field has been built, supported by recent studies of chemistry, geology, geophysics and thermal structure. The 3-D geoscience model presented in this paper illustrates the integration of multidisciplinary data to create a 3-D data-driven representation of the resource. This model and all its data will be used by the reservoir engineer to support the development and calibration of a reservoir simulation model. Various scenarios will be tested to provide the information needed by the policy makers to take informed decisions, backed up by strong scientific data.

In addition, the 3-D geoscience model of the Rotorua Geothermal Field provides a dynamic interface that allows the communication of scientific concepts to the community and illustrates the geothermal reservoir behaviour and response to utilisation.

REFERENCES

Alcaraz, S.A.: 3-D geological model of the Rotorua Geothermal Field, *GNS Science consultancy report 2014/289*. 2014.

Alcaraz, S.A., and Barber J.: A 3-D geological model of the Rotorua Geothermal Field. *Proceedings*, NZ Geothermal Workshop 37, Taupo. 2015.

Alcaraz, S.A., Orozco, G.: Geothermal data integration and data management best practices. XXV Congreso Annual de la Asociacion Geotermica Mexicana, Morelia, Mexico. 2018.

Allis, R.G., and Lumb, J.T.: The Rotorua Geothermal Field, New Zealand: its physical setting, hydrology, and response to exploitation. *Geothermics*, 21 (1/2), 7–24. 1992.

Ashwell, P.A., Kennedy, B.M., Gravley, D.M., von Aulock, F.W., and Cole, J.W.: Insights into caldera and regional structures and magma body distribution from lava domes at Rotorua Caldera, New Zealand. *Journal of Volcanology and Geothermal Research*, 258, 187-202. 2013.

Bay of Plenty Regional Council, Rotorua Geothermal Regional Plan, 1999.

Bibby, H.M., Dawson, G.B., Rayner, H.H., Bennie, S.L., and Bromley, C.J.: Electrical resistivity and magnetic investigations of the geothermal systems in the Rotorua area, New Zealand. *Geothermics*, 21(1/2), 43-64.1992.

Burnell, J.: Rotorua Geothermal Reservoir Modelling Part 1: Model Update 2004. Report to Environment Bay of Plenty. 2005.

Caldwell, T.G., Heise, W., Hill, G.J., Palmer, N.G., Bertrand, E.A., and Bennie, S.L.: Rotorua MT survey, additional data and updated 2-D modelling. *GNS Science consultancy report 2014/93*. 2014.

Climo, M., Milicich, S.D., Doorman, P., Alcaraz, S.A., Seward, A., and Carey, B.: Geothermal use inventory update – Data, visualization and information, *Proceedings*, World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020.

Crafar, W.M.: Geology of Rotorua City geothermal area. IN: Nairn, I.A.; Thompson, B.N.; Crafar, W.M.; Boielle, L.; Macdonald, W.J.P.; Glover, R.B. Geothermal resources survey: Rotorua geothermal district. Wellington: New Zealand Department of Scientific and Industrial Research. *DSIR geothermal report*, 1974.

Doorman, P., and Barber, J.: Rotorua Geothermal System – Current and Future Management. *Proceedings*, 39th New Zealand Geothermal Workshop 22 - 24 November 2017 Rotorua, New Zealand, 2017.

Giggenbach, W.F., and Glover, R.B.: Tectonic regime and major processes governing the chemistry of water and gas discharges from the Rotorua Geothermal Field, New Zealand. *Geothermics* 21 (1/2), 1992.

Gravley, D.M., Wilson, C.J.N., Leonard, G.S., and Cole, J.W.: Double trouble: paired ignimbrite eruptions and collateral subsidence in the Taupo Volcanic Zone, New Zealand. *Geological Society of America Bulletin*, 119(1/2), 2007.

Healy, J., Schofield, J.C., and Thompson, B.N.: Geological map of New Zealand 1:250,000 Sheet 5 Rotorua. 1st ed. Wellington: Department of Scientific and Industrial Research. Geological map of New Zealand 1:250,000 5. 1 fold map. 1964.

Heise, W., Caldwell, T.G., Bertrand, E.A., Hill, G.J., Bennie, S.L., and Palmer, N.G.: Imaging the Deep Source of the Rotorua and Waimangu Geothermal Fields, Taupo Volcanic Zone, New Zealand. *JVGR,* 314, 2016.

Hunt, T.M.: Gravity anomalies, caldera structure, and subsurface geology in the Rotorua area, New Zealand. *Geothermics*, 21(1/2), 1992.

Jongens, R., and Dellow, G.: The Active Faults Database of NZ: Data dictionary. Institute of Geological & Nuclear Sciences science report 2003/17. 2003.

Kissling, W.: Rotorua Geothermal Bore Water Level Assessment, *GNS Science Consultancy Report 2014/199*, 2014.

Lamarche, G.: Seismic reflection survey in the geothermal field of the Rotorua Caldera, New Zealand. *Geothermics*, 21(1/2), 1992.

Leonard, G.S., Begg, J.G., and Wilson, C.J.N. (compilers): Geology of the Rotorua area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 5. 1 sheet + 102 p. Lower Hutt, New Zealand. GNS Science. 2010.

Lloyd, E.F.: Geology of Whakarewarewa hot springs. Wellington: DSIR. Information series / Department of Scientific and Industrial Research 111. 24 p. 1975.

Macdonald, W.J.P.: Geophysical investigations of the Rotorua geothermal district. *IN:* Nairn, I.A.; Thompson, B.N.; Crafar, W.M.; Boielle, L.; Macdonald, W.J.P.; Glover, R.B. Geothermal resources survey : Rotorua geothermal district. Wellington: New Zealand Department of Scientific and Industrial Research. *DSIR geothermal report* 6. 1974.

Milner, D.M., Cole, J.W., and Wood, C.P.: Asymmetric, multiple-block collapse at Rotorua Caldera, Taupo Volcanic Zone, *New Zealand. Bulletin of Volcanology*, 64, 2002.

Milner, D.J., Cole, J.W., and Wood, C.P.: Mamaku Ignimbrite: a caldera-forming ignimbrite erupted from a compositionally zoned magma chamber in Taupo Volcanic Zone, New Zealand, *JVGR*, 122(3-4), 2003.

Neilson, G., Bignall, G., and Bradshaw D. :Whakarewarewa a Living Thermal Village – Rotorua, New Zealand. *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia, 25-29 April, 2010.

Ratouis, T.M.P., O'Sullivan, M.J., Alcaraz, S.A., and O'Sullivan, J.P.: The effects of seasonal variations in rainfall and production on the aquifer and surface features of Rotorua geothermal field, *Geothermics*, Volume 69, 165-188, 2017.

Ratouis, T.M.P., O'Sullivan, M.J., O'Sullivan, J.P.: A numerical model of Rotorua geothermal field. *Geothermics* 60, 105–125. 2016.

Reeves, R.R., Alcaraz, S.A., and Robson, B.: Mapping thermal features of the Rotorua Geothermal Field using aerial thermal infrared photography: 1988 vs 2014. *Proceedings,* 36th New Zealand Geothermal Workshop, 24–26 November 2014, Auckland, New Zealand, 2014.

Rogan, M.: A geophysical study of the Taupo Volcanic Zone, New Zealand. Journal of Geophysical Research. *Solid Earth and Planets*, 87(B5), 1982.

Seward, A.M., Reeves, R.R., Doorman, P., Sanders, F., Lor, S., MacDonald, N., Brackenrig, T., and Graham, D.: Surface Heat Loss Assessment of Rotorua Geothermal System, New Zealand. *Proceedings*, World Geothermal Congress 2020, Reykjavik, Iceland, April 26-May 2, 2020.

Scott, B.J., and Cody, A.D.: Response of the Rotorua geothermal system to exploitation and varying management regimes. *Geothermics* 29 (4/5), 2000.

Scott, B.J, Mroczek, E.K., Burnell J.G., SJ Zarrouk, Seward, A., and Robson, B.: The Rotorua Geothermal Field: An Experiment in Environmental Management, *Geothermics* 59, 2016.

Stewart, M.K., Lyon, G.L., Robinson, B.W., and Glover, R.B.: Fluid flow in the Rotorua Geothermal Field derived from isotopic and chemical data. *Geothermics* 21 (1/2), 1992.

White, P.A., Zemansky, G.M., Kilgour, G.N., Wall, M., and Hong, Y.S.: Lake Rotorua groundwater and Lake Rotorua nutrients phase 3 science programme technical report. *GNS Science consultancy report* 2007/220. 2007.

Wood, C.P.: A geological model of the Rotorua geothermal field. *IN*: Rotorua monitoring programme progress report : July-September 1984. Taupo: DSIR. 1984.

Wood, C.P.: Geology of the Rotorua geothermal system. *Geothermics*, 21(1/2), 1992.