A 3-D GEOLOGICAL MODEL OF THE ROTORUA GEOTHERMAL FIELD

S. Alcaraz[1], J. Barber[2]

[1] GNS Science, Wairakei Research Centre, Taupo 3377, New Zealand

[2] Bay Of Plenty Regional Council, Whakatane 3120, New Zealand

s.alcaraz@gns.cri.nz

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ABSTRACT

A 3-D geological model of the Rotorua Geothermal Field and surrounding area is built to better understand and visualise the geological setting of the field and provide a platform for future data integration to illustrate and model the geothermal reservoir behaviour and response to utilisation. Representative formations and faults are modelled using 3-D modelling and visualisation software Leapfrog Geothermal.

The Rotorua Geothermal Field covers an area of ~18 km^2 in the southern part of the Rotorua caldera, which formed during the eruption of the Mamaku Plateau Formation ~240,000 years ago. Pre-caldera domes surround the caldera and old ignimbrites outcrop to the south and west, although the exact nature, extent and thickness of deposits below the Mamaku Plateau Formation are unconstrained. Effusive eruptions followed the Rotorua caldera collapse, and rhyolitic dome complexes formed in the south-west of the caldera. A lake formed within the depression and an interlayered series of primary and re-sedimented tephra, alluvium and lacustrine sediments then covered the ignimbrite.

Faults are inferred throughout the field. The Rotorua caldera is located north-west of the Taupo Fault Belt rift and active faults are mapped south and north-east of the caldera rim, while the structures within the caldera have been buried under young sedimentary and volcaniclastic layers. Lineaments and alignment of thermal features are used to infer the location of several faults within the caldera. There is little geological evidence at depth to confirm the existence of most of these faults, although more than 1300 boreholes have been drilled in the area. Most wells are shallow (< 150 m drilled depth) and reliable geological data is scarce. Complimentary geophysical surveys (seismic, gravity, MT) are therefore used as indicators of the likely geological structures at greater depth.

1. INTRODUCTION

1.1 Objective

Bay of Plenty Regional Council (BOPRC) contracted GNS Science (GNS) to build a 3-D geological model of the Rotorua Geothermal Field. BOPRC provided their groundwater and geothermal well databases, which were complemented and validated with data from a literature review of the district (Alcaraz, 2014). Borehole data, surface geology and structures were then used to generate representative geological formations at depth using 3-D modelling software Leapfrog Geothermal v. 2.8.1.

The 3-D geological model of Rotorua presented in this paper is a first milestone in an integrated study of the Rotorua Geothermal Field. It provides a new and dynamic interface that will be used as a 3-D platform for complementary studies assessing the geothermal reservoir behaviour and response to utilisation. BOPRC aims for a new tool for reservoir management, supporting the long-term sustainability of the resource.

1.2 Geological setting

The Rotorua Geothermal Field covers an area of ~18 km^2 as defined by its shallow low resistivity signature (Bibby et al., 1992), which is typical of most large geothermal fields within the Taupo Volcanic Zone (Figure 1). It is located in the southern part of the Rotorua caldera, a roughly circular depression of ~17 km by ~19 km, which formed during the eruption of the Mamaku Plateau Formation ~240,000 years ago (Gravley et al., 2007). Also known as the Mamaku Ignimbrite, it is one of the most widely distributed ignimbrites of the Taupo Volcanic Zone (Milner et al., 2003). Older domes and ignimbrites outcrop outside the caldera structure; however there is little information available to define the exact nature, extent and thickness of pre-caldera deposits at depth in the Rotorua area. The Pokai Formation, mapped immediately south of the caldera is believed to be underlying the Mamaku Plateau Formation in most of the area. Post-caldera rhyolite dome complexes were emplaced in the south-west part of the caldera, area of maximum subsidence and likely source of the Mamaku Plateau Formation (Milner et al., 2002). A lake formed within the depression and a sedimentary sequence of mixed lacustrine, fluvial and volcanic deposits infilled the caldera. The level of the lake varied in time as younger eruptions from the near-by Okataina Volcanic Centre (OVC) 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. It reached its highest level after the eruption of the Rotoiti Formation and Earthquake Flat Formation at c. 61 ka (Wilson et al., 2007).

The Rotorua caldera is located about 10 km north-west of the Taupo Fault Belt that goes through Okataina (Figure 1). The Horohoro Fault marks the north-west boundary of the rift. It terminates less than 1 km south of the caldera wall. To the north-east, the Tikitere Graben (Thompson, 1974) intersects the caldera outline. No active structures are mapped within the caldera (Leonard et al., 2010; Langridge et al., 2015), as faults are most likely buried under young deposits. Intra-caldera structures are thought to channel fluids from the deep geothermal aquifer hosted in the Mamaku Plateau Formation to the surface. The shallowest aquifer sits in the Rotorua City domes. The lower beds of the overlying sedimentary sequence act as an aquitard.

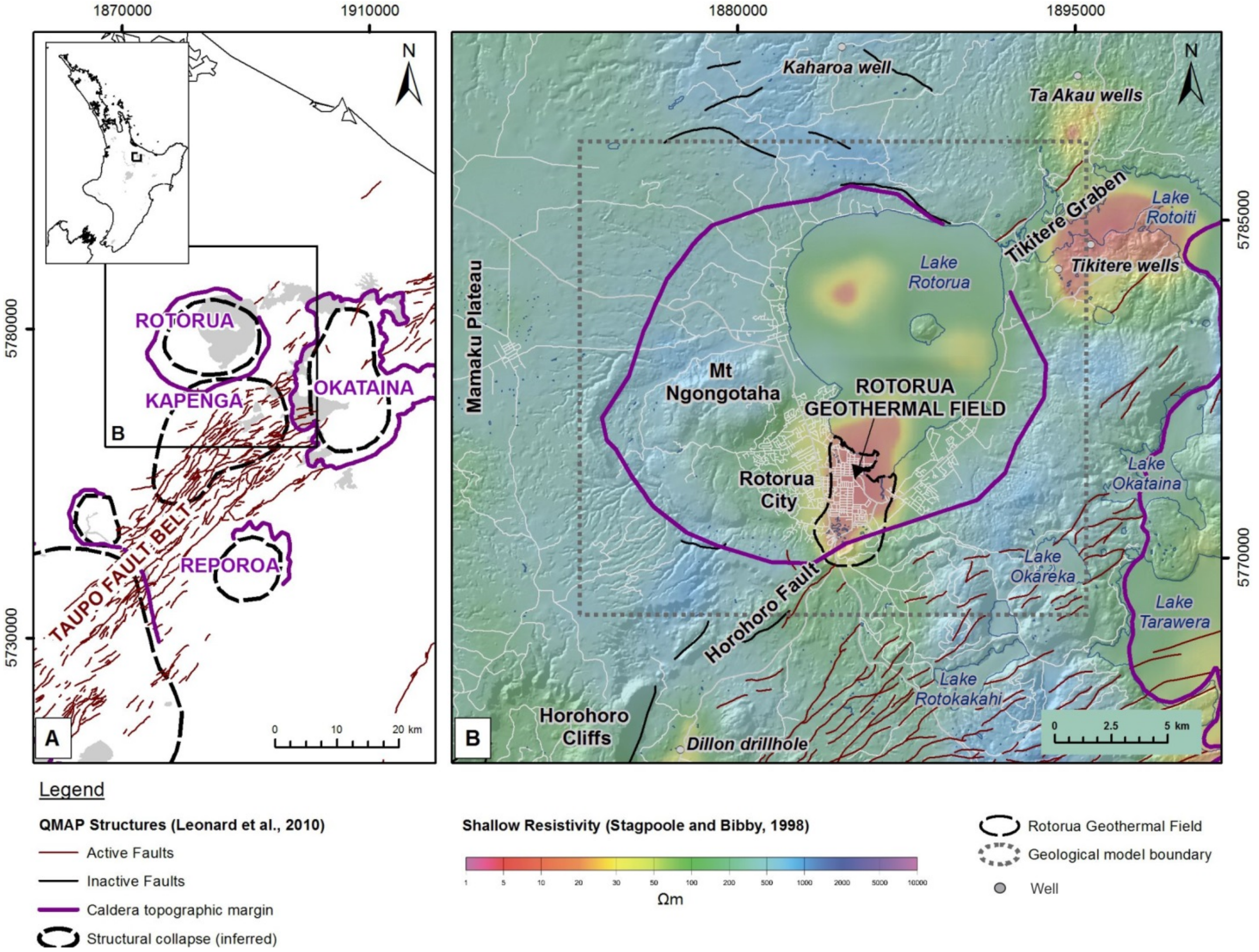

Figure 1: The Rotorua Geothermal Field location in its geological context. A. Map of the Rotorua caldera and major surrounding structures. B. Location of the Rotorua Geothermal Field within the Rotorua caldera, and its shallow resistivity signature. The indicative outline of the field is from BOPRC. Key locations mentioned in the text are labelled.

2. DATA

2.1 Borehole data

Drilling in Rotorua started in the 1920s, and more than a thousand wells have since been drilled in the immediate vicinity of the city. Most wells are shallow and do not exceed two hundred metres drilled depth. The deepest well in the city is RR892 at 458.8 m (Figure 2).

Drill cuttings and cores collection and description were not recorded systematically before 1978 (Wood, 1984). Geological descriptions, when available, mostly come from logs compiled by well drillers and are subject to the limitations of varying interpretations. Comparing data from these logs with reliable interpretation from professional geologists familiar with the Rotorua geology showed that these descriptions are often inconsistent, untrustworthy, and hence cannot be used systematically to define key lithologies and establish stratigraphic correlations (Alcaraz, 2014).

Comparatively few logs have been described by geologists. The first attempts at stratigraphic correlations within the Rotorua City area were carried by Crafar (1974) and continued by Wood (Wood, 1984; Wood, 1985; Wood, 1992) as part of the 1982 – 1985 Rotorua Monitoring Programme. Key formations identified by these authors are the Rotorua City domes, also referred to as the ‘Buried domes’, the Mamaku Plateau Formation and the Rotorua Basin Sediments that lie on top of the ignimbrite.

The Rotorua City domes are one of the post-caldera rhyolite complexes and have been intersected by > 100 drillholes (Figure 2). Both domes form a N-S elongated ridge, separated by a saddle, which only outcrops on the eastern side of Pukeroa (“Hospital Hill”) and is elsewhere buried beneath sediments and breccias (Crafar, 1974; Wood, 1984; Wood, 1985; Wood, 1992). The base of the domes has never been intersected. Their total thickness is unknown but constraints are given by wells RR918 and RR892 that intersected respectively 219 m and 400 m of rhyolite, the latest from the likely combination of the Rotorua City Domes and Ngongotaha Dome. While unproven, it is most likely that the rhyolite domes lie on the Mamaku Plateau Formation which must have infilled the entire caldera depression at time of deposition.

The upper units of the Mamaku Plateau Formation 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 in RR784A (Wood, 1983; Wood, 1992). Other bores indicate variation in the depth of the ignimbrite, its surface dropping by ~165 m towards the north, from its shallowest known occurrence in RR724 (210 mRL) to its deepest known occurrence in RR889 (47 mRL).

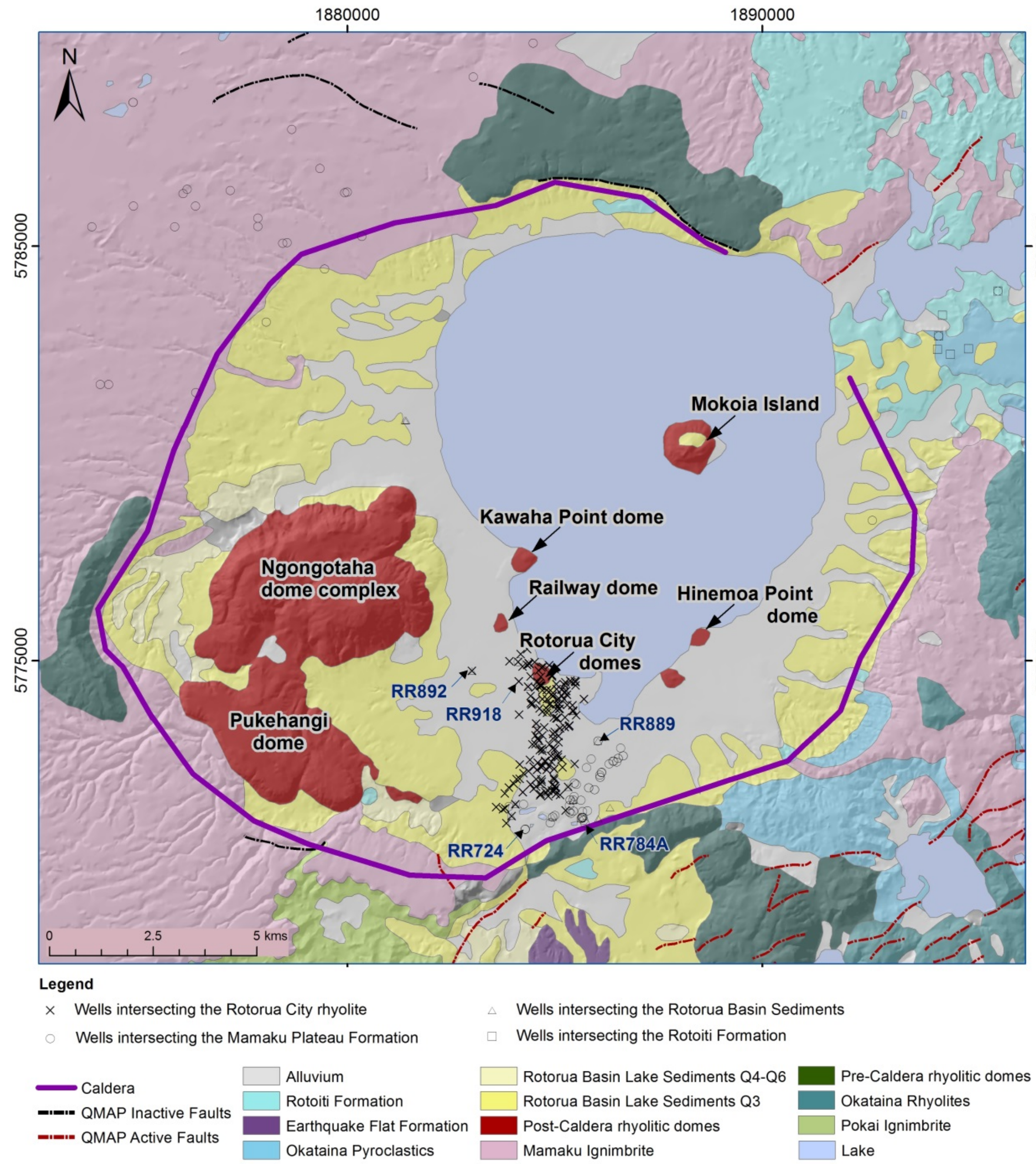

Figure 2: Geological map of the Rotorua area (modified from Leonard et al., 2010). Key boreholes with trusted geological data are displayed. Locations mentioned in the text are labelled.

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 RR889. For the model purposes the QMAP classification was used and the sediments, belonging to the Tauranga Group, are subdivided in two units based on their respective age group of Middle Pleistocene and Late Pleistocene.

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 Plateau Formation. These include the Te Akau wells (Kaituna River Hydro Schemes; Thompson, 1964), 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 (Figure 1 and Figure 2 for locations). Wells from the Taheke Geothermal Field are proprietary and have not been included in this study.

Considering the wider Rotorua area, a total of 1317 wells have been centralized in a new Rotorua borehole database and loaded in Leapfrog Geothermal. Only trusted geological records have been used as direct input to the 3-D geological model to constrain key stratigraphic surfaces and establish sub-surface correlations.

2.2 Surface data

The Digital Terrain Model (DTM) used for the 3-D model has been compiled from the mosaicking of a 2 m resolution regional DTM of the Rotorua district with high resolution Lidar data covering the Rotorua Geothermal Field area, both datasets supplied by BOPRC. Bathymetry contours of Lake Rotorua have also been provided.

The geology of the Rotorua district was mapped at the 1:250,000 scale by Healy et al. (1964) and most recently by Leonard et al. (2010). The latest is largely consistent with more detailed mapping carried out by other authors (e.g. Thompson, 1974; Milner, 2001). The digital outline of formation boundaries and main structures from the Rotorua QMAP sheet have thus been used as input in the model. This dataset does not have any mapped structures within the caldera. Intra-caldera faults postulated by Llyod (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.

2.3 Geophysical data

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

2.3.1 Seismic profile

Lamarche (1992) presents the results of a seismic reflection survey done in the south-eastern part of the Rotorua Geothermal Field. Key horizons have been correlated to known stratigraphic layers from nearby wells (Wood, 1992), including the top surface of the lacustrine sediments of the Rotorua Basin Sediments unit, the top surface of the Mamaku Plateau Formation, and the possible contact between the Mamaku Plateau Formation 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).

2.3.2 Magneto-telluric profiles

A recent MT survey provides insights on the deep-resistivity structure of the Rotorua Geothermal Field (Caldwell et al., 2014). MT profiles were imported in Leapfrog and used as a guide to constrain the location of key features as identified by these authors, in particular the inferred location of the caldera floor and caldera margins based on sharp contrast between zones of high resistivity (basement) and low resistivity (old ignimbrites and/or altered rock of the reservoir area).

2.3.3 Gravity data

The gravity signature of the Rotorua area is characterised by a gravity high below the city and a gravity low west of the lake with three minima (Hunt, 1992). The gravity high matches the geometry of the buried Rotorua City domes, and provides additional insights on the lobes geometry of theses domes 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 Plateau Formation (Rogan, 1982). It also indicates that there is no rhyolite at depth in this area (Hunt, 1992).

3. MODELLING

3.1 Model boundary

The 3-D geological model of Rotorua has been designed to help understand the characteristics of the geothermal field in its regional geographical and geological context. The area of interest (AOI) constraining data input and model extent was defined to capture key geological features likely to influence the geothermal reservoir. The boundary was thus set to enclose the Rotorua Caldera.

3.2 Structures

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 (Thompson, 1974). The caldera outline from Leonard et al. (2010) was used and modelled as a sub-vertical structure (Figure 3). Other faults from Leonard et al. (2010) include the Ngakuru Fault and Opawhero Fault, simplified as one structure, and the Whakapoungakau Fault and Horohoro Fault, identically simplified to one structure. They represent the westernmost faults of the Taupo Fault Belt in this area and both dip to the south-east. Due to software constraints, the Tikitere Graben northern boundary has been associated to the QMAP inactive, and unnamed, fault located north of the caldera rim. This structure is sub-vertical with a downthrown block to the south. It terminates on the caldera wall.

Faults modelled within the caldera are less constrained. Lloyd (1975) inferred faults from lineaments of springs and geysers in the Whakarewarewa area. Three of these faults are included in the model: the Pohaturoa, Whakarewarewa and Puarenga faults. Wood (1984) introduced the concept of the Inner Caldera Boundary Fault (ICBF) to account for the deepening of the Mamaku Plateau Formation based on bore data. The ICBF has been confirmed as a fault zone including at least 4 normal faults (Lamarche, 1992), however, for the purpose of the model it was modelled as a single structure.

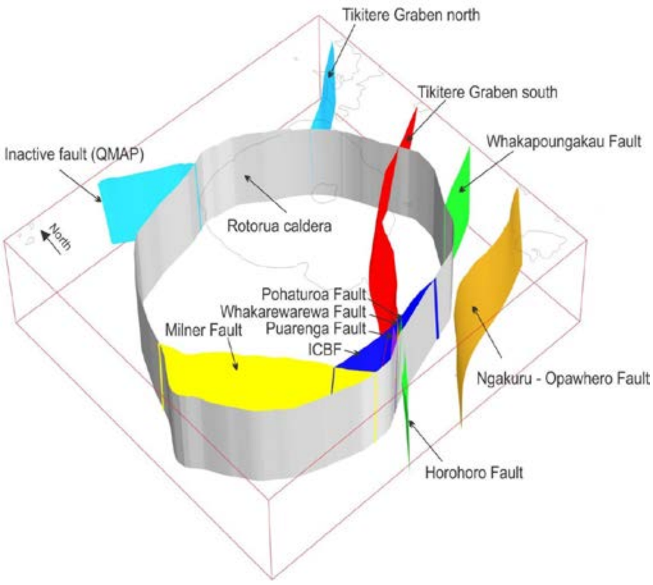

Figure 3: Structural network of the 3-D geological model of the Rotorua Geothermal Field presented in this study.

The relationship between the Rotorua caldera and the Tikitere Graben is not well established. The southern boundary of the Tikitere Graben defined by Milner (2001, 2002) intersects the caldera wall. To meet the requirements of the software, the Tikitere Graben southern boundary is linked to the hypothesised Ngapuna Fault from Simpson (1985). This structure dips to the north-west. Finally, Milner's interpretation of an inherited NW-SE basement structure has been included in the model. It marks the northern boundary of the Pukehangi dome.

It is believed that more faults are present at depth in the Rotorua caldera; however there are not enough constraints to locate them with certainty. Faults that we could not justify or which geometries could not be rendered have not been included in the model.

3.3 Stratigraphy

Geological formations included in the model are selected to best represent the local geology based on our current understanding of the area. The size of the model, the resolution used and the amount and quality of geological data available dictates which formations can be or should be modelled. In an area the size of the current model, formations of limited extent and/or limited thickness cannot be realistically modelled. Formations at depths with unknown extent due to limited borehole data should not be modelled in too much detail either. Following these considerations and our understanding of the geology of Rotorua from the data available, a selection of 12 units was modelled (Table 1).

Table 1: List of the modelled units from youngest to oldest, and constraints used to create them.

MODELLED UNITS	FORMATIONS	MODEL CONSTRAINTS
Alluvium	Surficial deposits	Surface outlines Modelled as unfaulted
Okataina Pyroclastics	Undifferentiated ignimbrites from OVC	Surface outlines Modelled as unfaulted
Rotoiti Formation	Rotoiti Formation	Surface outlines Borehole constraints (Tikitere area) Modelled as unfaulted
Earthquake Flat Formation	Earthquake Flat Breccias	Surface outlines Modelled as unfaulted
Rotorua Basin lake Sediments • Q3 Late Pleistocene • Q4-Q6 Middle Pleistocene	Undifferentiated re-sedimented tephra, alluvium and lacustrine sediments	Surface outlines Thickness constrained by some boreholes Modelled as unfaulted
Post-caldera Rotorua rhyolites	Ngongotaha dome, Pukehangi dome, Kawaha Point dome Railway dome, Rotorua City domes, Mokoia Island dome Hinemoa Point dome	Surface outlines Borehole constraints (Rotorua City domes area) Gravity map Modelled as unfaulted
Mamaku Ignimbrite	Mamaku Plateau Formation	Surface outlines Borehole constraints (in and out of the caldera) Seismic profile Modelled as faulted: thickness of the formation and offset across each fault are estimated
Okataina rhyolites	Whakapoungakau dome and other domes from OVC	Surface outlines Modelled as faulted: depth, thickness and offset across each fault are estimated
Pre-caldera rhyolites	Hamurana dome, Fryer dome Endean dome, Pohaturoa dome	Surface outlines Modelled as faulted: depth, thickness and offset across each fault are estimated
Pokai Ignimbrite – Pokopoko Formation	Pokai Formation Pokopoko Breccias	Surface outlines (localised to the south) Borehole constraints (Tikitere and northern wells) Modelled as faulted: depth, thickness and offset across each fault are estimated in area without constraints
Old ignimbrites (> 300 ka) including Whakamaru Group	Whakamaru Group ignimbrites, Chimp Formation, Matahina Formation, undefined local and regional deposits	No outcrops and no constraints from borehole data in the model boundary Modelled as faulted: depth, thickness and offset across each fault are estimated
Basement	Waipapa/ Torlesse (composite) terrane	No outcrops and no constraints from borehole data in the model boundary MT used to define depth to basement (caldera floor) Modelled as faulted: depth of the surface and offset across each fault are estimated

3.4 Rotorua Geological Model

The 3-D Geological model presented here results from the combination of the modelled faults and contact surfaces created for each stratigraphic unit. Each resulting volume represents a geological formation (Figure 4).

The basement depth within the caldera is controlled by Caldwell et al. (2014) interpretation of the caldera floor. The distribution of the Mamaku Plateau Formation is well defined by outcrops and its depth constrained by borehole data in the south-east of the geothermal field, which is validated using Lamarche (1992) seismic profiles. This author also postulates a maximum thickness of 279 m. The ignimbrite is known as > 200 m thick in Tikitere and 145 m thick in the Kaharoa well. It is expected to be considerably thicker within the caldera and the modelled base of the ignimbrite is thus deeper than Lamarche's interpretation. The post-caldera Rotorua rhyolites are well-constrained from surface data and borehole data below Rotorua City. Uncertainty remains whether these rhyolites complexes are connected at greater depth. The Rotorua Basin Sediments thickness is locally well constrained in the Rotorua area, however, poor borehole data quality and the high variability in the nature of sediments both laterally and vertically preclude lateral correlations of key sedimentary strata, hindering any detailed modelling. The sediments were modelled as a single formation, subdivided by age in two units as per the QMAP classification.

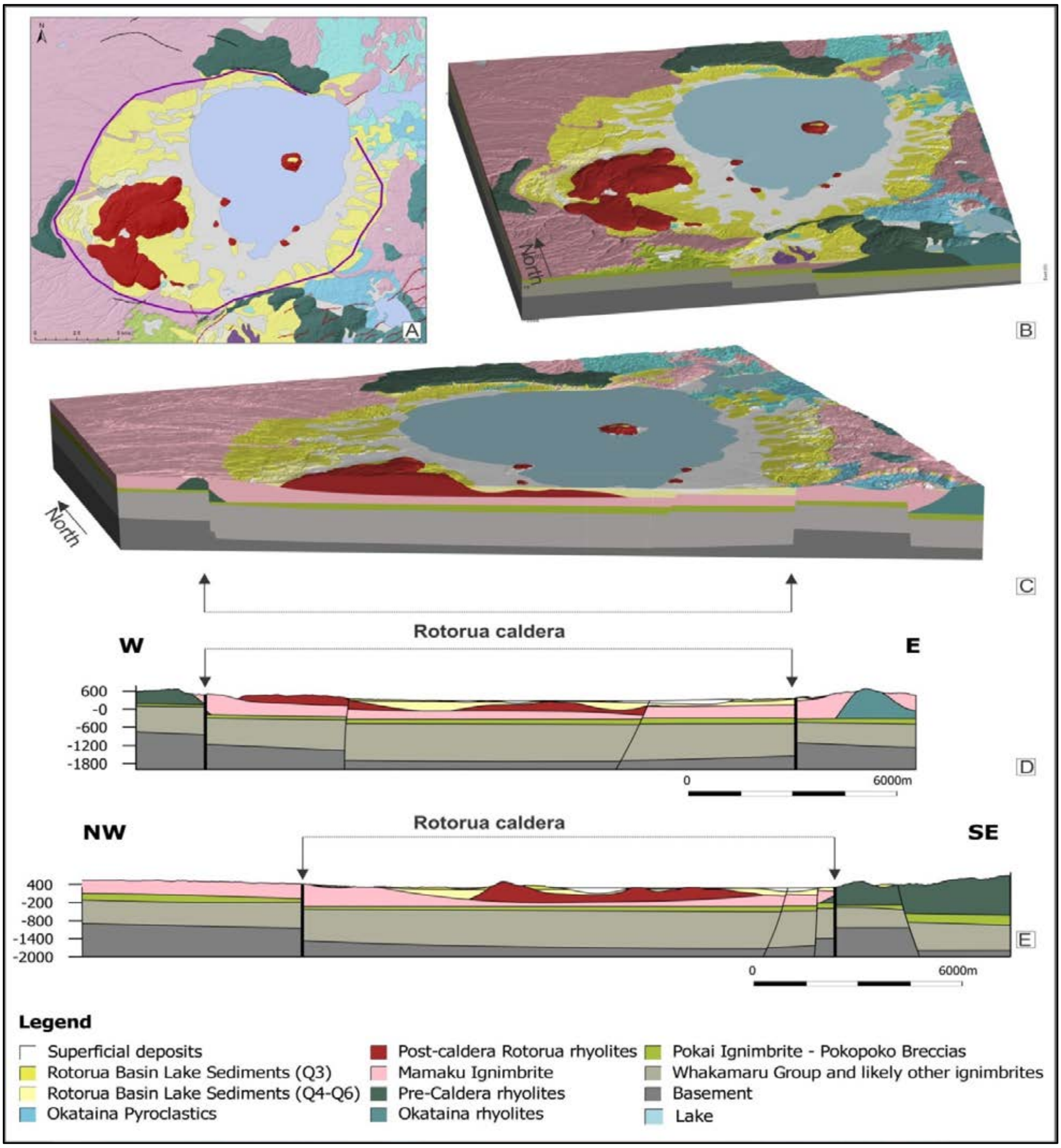

Figure 4: 3-D geological model of Rotorua. A. Original geological map at surface. B. 3-D view of the Model. C. WNW-ESE slice through the model. D and E: Cross-sections through the model.

4. CONCLUSION

The 3-D geological model of the Rotorua Geothermal Field presented here is built using borehole data provided by BOPRC and complemented by a thorough literature review of the area. All data found in the literature have been included in the borehole database created as part of this project and used as input to generate the model. Many boreholes have been drilled in the Rotorua area, but the amount of useable geological data is comparatively small. The surface geology is well documented and different authors agree on the distribution of the formations at surface. The QMAP dataset was used as input to build contact surfaces. On the other hand, the structural interpretations vary between authors and the model integrates information from various sources, taking into account the resolution of the model, data availability and the capabilities of the software.

Further work could be done to refine the model in the future. While the hydrology of the system is overall well understood, the relationships between the deep Mamaku Plateau Formation aquifer and shallow Rotorua rhyolites aquifer could be improved. 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 understanding the Rotorua Geothermal Field rock type distribution.

The 3-D geological model of Rotorua is a first step towards building a comprehensive model of the Rotorua Geothermal Field. Leapfrog Geothermal provides the capabilities to integrate multi-disciplinary data in one interface and this model should be the foundation for further data integration, including a link with reservoir models of the geothermal field.

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