Refining geological models through 3D gravity modelling at Wairākei, Tauhara and Rotokawa geothermal fields

Jenny Barretto[1], Craig Miller[2], Lucy Carson[2] and Samantha Alcaraz[2], Isabelle Chambefort[2]

[1]GNS Science, Avalon Research Center, 1 Fairway Drive, Avalon 5010, New Zealand

[2]GNS Science, Wairākei Research Centre, 114 Karetoto Road, RD4, Taupō, 3384, New Zealand

j.barretto@gns.cri.nz

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ABSTRACT

Three-dimensional forward and inverse modelling of gravity data from Wairākei, Tauhara and Rotokawa geothermal fields were undertaken to reconcile geological models with geophysical observations. Our aim is to improve areas of the geological model unconstrained by drilling through utilising geophysical information. We developed a starting geological block model using well log data where each geological unit is assigned a density based on petrophysical data. We converted the block model into a vertical prism (VP) model for geophysical modelling. Initial forward modelling of the VP model showed a large misfit between observed and calculated gravity in several areas indicating areas where the geological model did not match geophysical data. To improve the fit, we undertook inversion modelling. Gravity inversion was performed on the VP model in three ways: 1) geometry inversion of basement depth in areas with no well data; 2) homogeneous inversion to get best fit densities distributed uniformly within geological units, and 3) heterogeneous inversion where density distribution was allowed to vary within each geological unit. The resulting geological model shows that greywacke basement is probably present beneath Wairākei at >3000 m depth. The model also suggests the presence of a low-density vertical zone cutting through the Rotokawa Andesite and underlying greywacke interpreted to be a buried vent focusing fluid flow and manifesting on the surface as Lake Rotokawa. Other minor refinements to the geological model were made that are consistent with gravity observations. We show that refinement of geological models through forward and inverse modelling of dense geophysical datasets helps enhance subsurface models and guide future drilling plans.

1. INTRODUCTION

Three dimensional geological models have become standard tools in exploration and development of geothermal resources because they help visualize spatial relationships of often complex geoscience datasets (Witter and Melosh 2018; Zhu et al. 2020; Brown 2022) and can be directly used in numerical heat and fluid modelling (Milicich et al., 2017). Geological models are traditionally built by integrating information mainly from geological and structural maps, and well log data (Teng and Koike 2007; Alcaraz et al., 2011). Geophysical data, when available, are often analysed separately (e.g., for presence of faults, fluid movement, basement depth) and are added into geological models if consistent with what is seen in well data. For example, fault trace locations are added as suggested by magnetic or seismic reflection data, but displacements are dictated by lithological offsets shown in wells (Zengerer et al., 2010). Geological models are seldom further tested for consistency with petrophysical data (e.g. rock densities) and geophysical observations, such as by performing gravity forward and inverse modelling (Guglielmetti et al., 2013; Witter et al., 2016), even if models include large areas unconstrained by drilling and have good geophysical data coverage.

This paper describes the benefits of using 3D gravity forward and inverse modelling to test areas of geological models unconstrained by drilling as applied to the Wairākei, Tauhara and Rotokawa geothermal fields. These fields are near each other, have relatively dense coverage of gravity measurements, have varying spatial distribution and depths of wells (Figure 1).

2. DATA AND METHODS

This section describes the data used in building the initial 3D geological model and in 3D gravity modelling which includes both open-source and proprietary data (per communication from Mercury NZ Limited and Contact Energy 2020).

2.1 3D geological modelling

We built a simplified 3D Wairākei-Tauhara-Rotokawa geological model using data from 331 geothermal and monitoring wells (number includes well sidetracks) – 51 at the Rotokawa field and 280 at the Wairākei-Tauhara field. The model covers an area of ~407 km2 (23 x 18.5 km) and extends to a depth of 5600 m (elevation relative to sea level).

Geological units were modelled in Leapfrog Energy software (https://www.seequent.com/products-solutions/leapfrog-geo/) using logged geological intervals, by generating 3D surfaces that represent the upper and lower contact of each unit. To simplify the model for geophysical modelling, formations with similar physical properties were grouped into single larger units – e.g., various rhyolite lava bodies grouped into one larger rhyolite unit. In areas where well data was not available (e.g., at depth or areas with few wells), geological surfaces were extrapolated by the software and, where necessary, edited manually using user-generated polylines to create a geologically realistic model.

We constructed a simple network of 11 faults using data from faults mapped at surface (NZ Active Fault Database; GNS Science, 2016) and offsets between geological formations in wells. Shallower units (i.e. Waiora Formation and above) do not show significant fault offsets, so offsets of deeper formations (Whakamaru Ignimbrite, Tahorakuri Formation, Torlesse Greywacke) were used to constrain major fault locations. When activated, the fault network divided the model into 24 domains (fault blocks), which show the observed and inferred faulted offsets of the deeper geological units. A notable feature of the model is the absence of

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greywacke basement in the western part (Figure 2A) as the unit has never been intercepted by drilling in this area.

The 3D geological model was converted into a block model (100 x 100 x 100 m cell size) for use in the gravity modelling software Geoscience Analyst Pro (https://www.mirageoscience.com/mining-industry-software/geoscience-analyst/pro/). Each rock unit was assigned a starting density contrast (Table 1), which was the mean of a range of densities of each rock unit subtracted from 2.67g/cm^3 (density of greywacke basement and the Bouguer correction density), except for greywacke that was assigned a density of 0 g/cm^3. Densities are from well core measurements and Tenzer et al., (2011). For geophysical modelling, the block model was then transformed into a vertical prism (VP) model wherein each rock unit is divided into100 x 100 m vertical prisms while retaining the assigned rock density contrast distributed homogeneously within each prism. The geophysical model is encapsulated in a half-space assigned to capture long wavelength features. The process from building a 3D geological model to converting into a VP model with assigned density contrasts was repeated in making the final iteration of the model (Figure 2B).

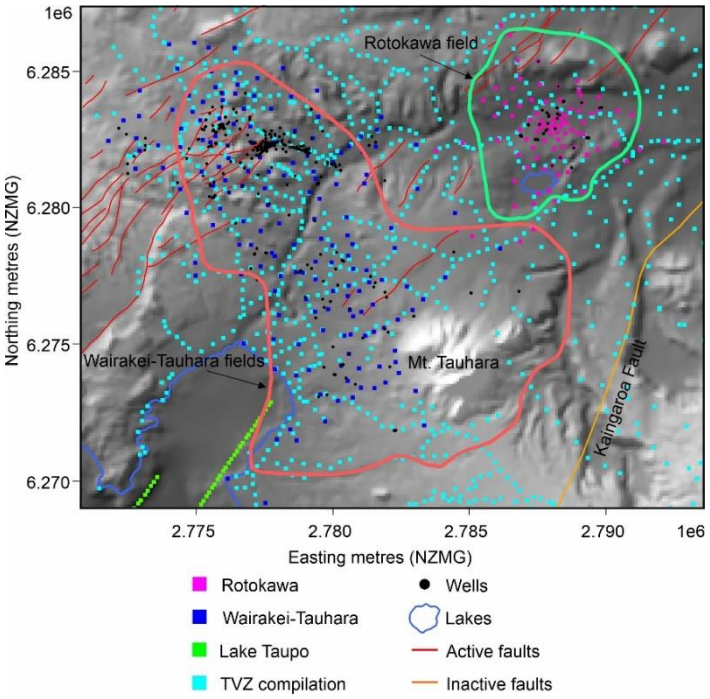


Figure 1: Map of study area showing gravity stations in squares, well locations as black dots, faults (GNS Science, 2016), and geothermal field boundaries (NZGA 2018). Background topography is a combination of LiDAR data from Waikato Regional Council and 8m digital elevation model (LINZ, 2012)

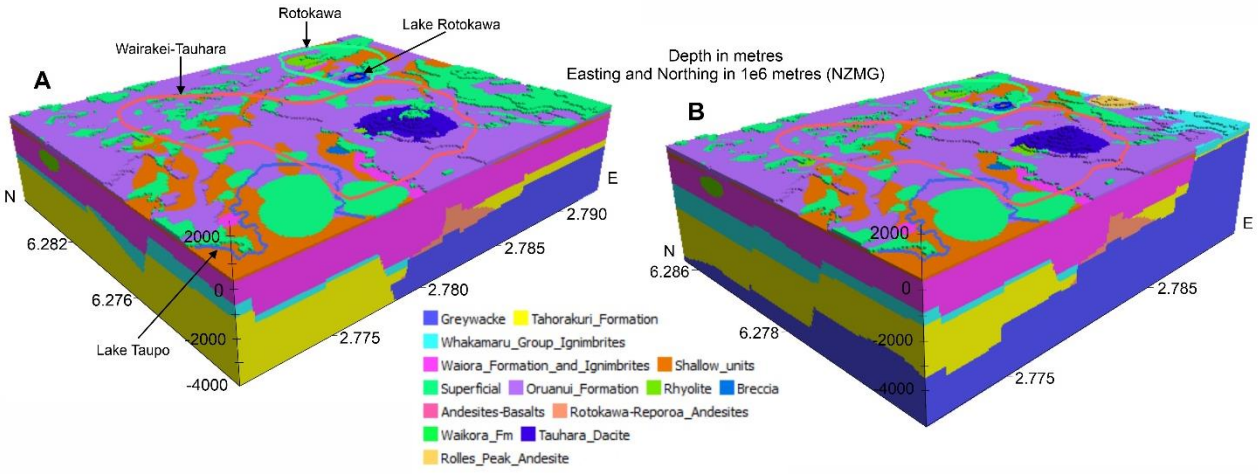


Figure 2: A. Starting 3D geological model built using only logged geological intervals from wells and fault traces. B. Final model, which included elevation changes as suggested by 3D gravity modelling. Outlines of geothermal fields and lakes are overlain.

Table 1. Density contrasts assigned to geological units and density contrast recovered from homogeneous gravity inversion (last column) relative to 2.67 g/cm^3. All values are in g/cm^3.

Unit	Starting	Final	Lower Bound	Upper Bound	Homogeneous inversion "best fit" density contrast
Andesites-Basalts	-0.47	-0.002	-1.17	0.23	-0.78
Breccias	-0.535	-0.015	-1.35	0.28	-0.88
Greywacke	0	0	-0.17	0	0.25
Oruanui Formation	-0.865	-0.865	-0.88	-0.85	-0.58
Rhyolites	-0.634	-0.4	-1.1189	-0.15	-0.31
Rolles Peak Andesite		-0.05	-0.38	-0.02	0.32
Rotokawa-Reporoa Andesites	-0.2	-0.18	-0.38	-0.02	-0.30
Shallow Units	-1.12	-0.6	-1.87	-0.37	-0.82
Superficial	-1.215	-1.215	-1.38	-1.05	-0.02
Tahorakuri Formation	-0.32	-0.38	-0.57	-0.07	-0.12
Tauhara Dacite	-0.19	-0.1	-0.29	-0.09	-0.74
Waikora Formation	-0.11	-0.051	-0.27	0.05	0.25
Waiora Formation and Ignimbrites	-0.755	-0.4	-1.37	-0.14	-0.19
Whakamaru Group Ignimbrites	-0.27	-0.06	-0.48	-0.06	-0.09

2.2 3D gravity modelling

We used gravity data from the TVZ compilation of Stagpoole et al (2020) that includes the Lake Taupo gravity data of Davy and Caldwell (1998) and from microgravity surveys of Wairākei, Tauhara geothermal fields provided by Contact Energy Limited and Mercury NZ Limited (Figure 1). Data were reprocessed for consistency using Oasis Montaj software (https://www.seequent.com/products-solutions/geosoft-oasis-montaj/) to generate Bouguer anomalies. Lake Taupo data which had an additional correction for density of water, was imported as is from the TVZ compilation. Gravitational effect of topography on each observation site was accounted for by applying Bouguer plate and terrain corrections using a density of 2.67 g/cm^3, representing the greywacke basement exposed in places west and east of the TVZ and intersected in some deep wells (>2 km).

A regional gravity field calculated by Stagpoole et al (2020) was subtracted to obtain residual Bouguer anomalies (Figure 3A) that reflect gravity signatures of the upper crust and remove gravity effects of lower crustal and mantle structure.

Forward gravity modelling was performed on the starting VP model to calculate its gravity effects and the misfit with observed gravity values. To improve the fit, inverse gravity modelling was performed in three ways:

- Geometry inversion. Vertical boundaries between geological units were allowed to move while density contrasts within units were kept constant. This inversion helps determine which parts of the model may need to be elevated, moved down or change dimensions. Nine Rotokawa wells that intersected greywacke were used as elevation constraints.

- Homogeneous inversion. The VP model was inverted for the best fit densities of each geological unit, keeping the geometry fixed. This inversion helps determine what density contrast should be assigned to each unit.

- Heterogeneous inversion. Density distribution was allowed to vary within each geological unit but limited to assigned lower and upper bound values (Table 1). This was applied to the geological model's second iteration and generated the lowest misfit.

3. RESULTS AND DISCUSSION

Forward modelling of the starting geological VP model resulted in calculated gravity values that have significant misfit (RMS = 9.48 mGal) with observed gravity (Figure 3B). Misfit is defined as the observed – calculated gravity value and a positive misfit indicates mass deficit, while a negative misfit indicates mass surplus in the model. Clustered positive misfit values (mostly between 8 to 15 mGal) were observed over the central southwest and southeast quadrant of the model. In these areas densities of rock units must increase, or the mass of rock units must increase. An obvious cluster of negative misfit values (mostly -4 to -15 mGal) were observed over the northeast quadrant, northern edge, and southwest corner which implied the need to decrease rock densities, move down elevation of top of the basement or decrease the mass of major units.

Increasing or decreasing the density of a rock unit meant changing the density by the same amount throughout its extent because density is distributed homogeneously. Simply changing unit density did not adequately fit the observed data implying changes in the geometry of the units are necessary.

3.1 Geometry inversion

Result of the geometry gravity inversion (Figure 4) showed there is likely greywacke basement in the central southwest area at depths ~2000 to 3000 m below sea level (mbsl) and in the northwest at about 3000 mbsl where wells have not intercepted greywacke. In the southeast quadrant, the greywacke was elevated from 1500 mbsl to about 1000 mbsl and 100 mbsl. Along the northern edge of the model, basement dropped to 5000 mbsl and 8000 mbsl from east to west. In places unconstrained by Rotokawa wells in the northeast quadrant, greywacke dropped by 400 m to 1000 m. A huge drop to 10 km below sea level was modelled for the

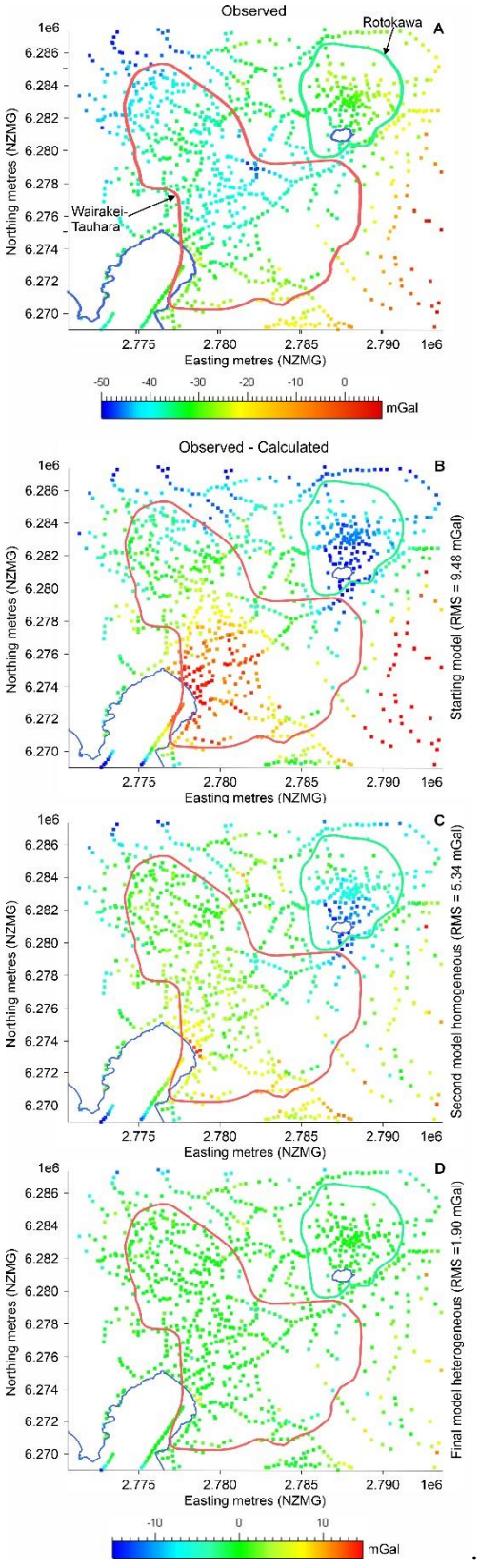


Figure 3: A. Residual Bouguer anomalies (observed gravity values). B. Starting model misfit. C. Model misfit from homogeneous density distribution. D. Final model misfit from heterogeneous density distribution. Misfit is the difference between a model's observed and calculated gravity values.

southwest corner where Lake Taupo is located. Basement depths below 5000 mbsl imply presence of thick low density units overlying basement. The very few gravity measurements over Lake Taupo also likely affected the modelling results in this area as the model is poorly constrained by data (Figure1).

Elevation changes of greywacke were considered in making the second and final iteration of the 3D geological model (Figure 2B and Figure 5). Due to greywacke's high density and extent, making the appropriate changes in their geometry (while keeping changes to overlying units within constraints imposed by wells and faults displacements) should reduce the gravity misfit. Faults trending NE-SW that cut the eastern side of the model were extended to the western side and the inactive Kaingaroa Fault was added (Figure 5). The drop in basement elevation at the southwest corner was not applied to the geological model because there is no structure that would accommodate the displacement. Rolles Peak Andesite, which was not in the starting model because it did not have a well through it, was added on the surface to the east where it outcrops (Figure 2B).

3.2 Homogeneous inversion

To further reduce the gravity misfit of the second model, recovered best-fit density contrasts (Table 1) from the homogeneous gravity inversion were used as guide in adjusting density contrast of each unit in the geological model. Recovered density contrasts that fell outside the measured lower and upper bounds were not used (e.g., 0.25 g/cm^3 for greywacke and -0.74g/cm^3 for Tauhara Dacite).

Density contrasts were incrementally changed one geological unit at a time beginning with large units (e.g. Tahorakuri Formation and Waiora Formation and Ignimbrites). Forward gravity modelling was applied after each density contrast adjustment to see the gravity response until the lowest RMS misfit was achieved (5.34 mGal; Figure 3C). Density contrasts used in the last adjustment are listed under "Final" column in Table 1. Comparison with the starting model's misfit plot (Figure 3B) shows the positive misfit in the central southwest and southeast quadrants were reduced but an increase was observed at the middle southern edge (about 2.785e6 East). The previous negative misfit along the northern edge of the model was reduced but only a minimal reduction was observed in the northeast quadrant. There was no apparent change at the southwest corner because the dense basement was still elevated.

It was also observed that although density adjustment in Rotokawa-Reporoa Andesite reduced the negative misfit over the northeastern andesite body, it also caused an increase in positive misfit over the southern andesite body (Figure 3C and Figure 5). This indicated that the two andesite bodies have significantly different density contrasts. This could be addressed in two ways: 1) by a third iteration of the 3D model with Rotokawa-Reporoa Andesites split into two geological units and assigning a higher density contrast to the southern unit, or 2) by heterogeneous inversion allowing the density distribution to vary within geological units, which was the preferred option.

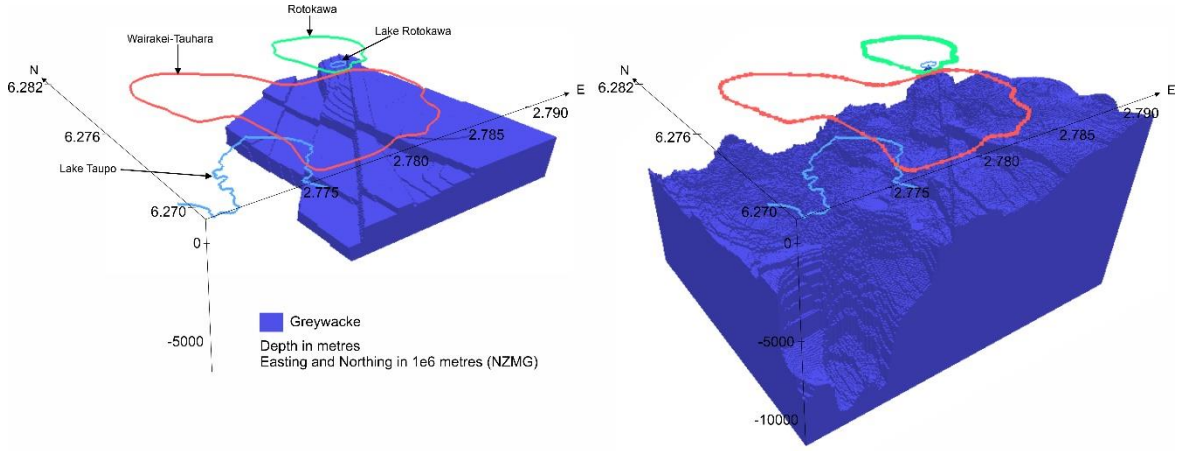


Figure 4: Elevations of greywacke before (A) and after (B) geometry inversion of starting geological VP model. Note the large drop in basement in the southwest corner, in an area of sparse gravity data, which is not carried into the final model.

3.3 Heterogeneous inversion and final model

Using the final density contrasts from Table 1, as a starting point, heterogeneous inversion was applied to the 3D model. Density contrast was allowed to vary laterally and vertically in each geological unit but within lower and upper bounds (Table 1). This resulted in RMS misfit of 1.90 mGal (Figure 3D). Negative misfit remained over the northwest and southwest corners implying the greywacke elevation may be lower than 5000 mbsl and 3900 mbsl, respectively (Figure 5) or less dense plutonic bodies which are parts of caldera-related magmatic systems may be present at those depths (Barker et al., 2021). Positive misfit remained over the southeast corner indicating greywacke may be shallower than modelled or a shallow high-density body above basement is missing from the model.

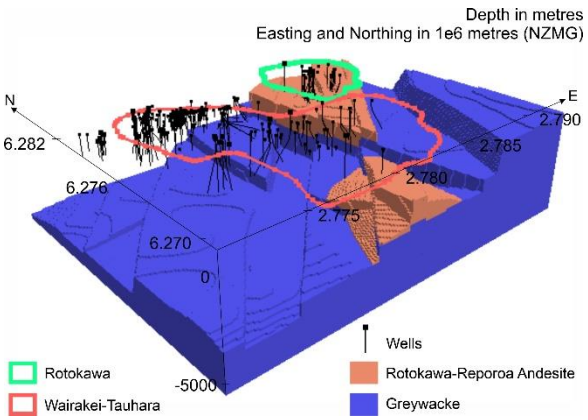


Figure 5: Interpreted extent of greywacke in the final model and locations of Rotokawa-Reporoa Andesite bodies. Outlines of geothermal fields are overlain.

Heterogeneous inversion improved the gravity misfits over the Rotokawa-Reporoa Andesite (Figure 3D) and resulted in a southern block with less negative density contrast than the northeastern block (Figure 6). The northeastern block's more negative density contrast could be due to a more intense hydrothermal alteration (Rae et al., 2011; Siratovich et al., 2014).

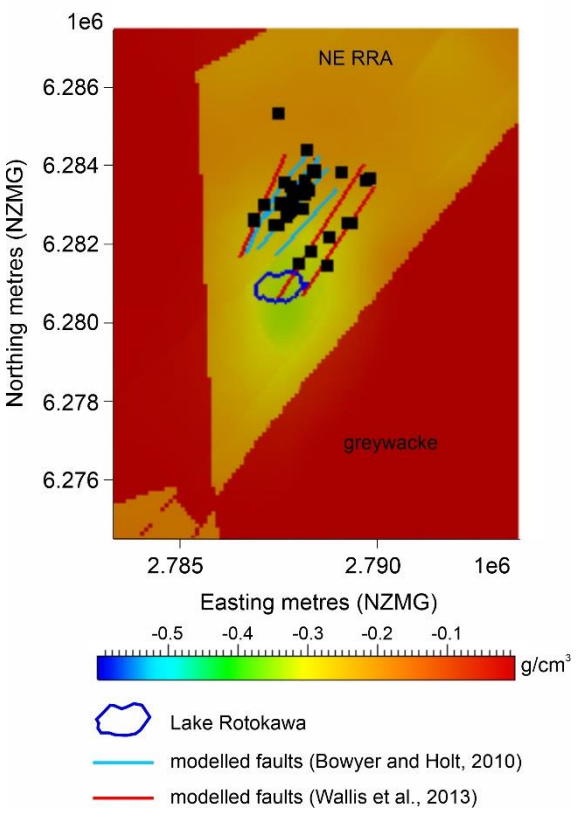


Figure 6: Focused low-density zone in northeastern Rotokawa-Reporoa Andesite (NE RRA) unit aligned with Lake Rotokawa on the surface.

A focused low-density zone was also observed in the northeastern Rotokawa_Reporoa Andesite block at about 900 mbsl and through greywacke at 1800 mbsl (Figure 6). It could indicate a more concentrated intense hydrothermal alteration relative to other parts of the andesite. This low-density zone, located south of modelled NE-SW trending

faults (Bowyer and Holt, 2010; Wallis et al., 2013), appeared to align with Lake Rotokawa and could imply existence of a vent through the andesite facilitating fluid flow up towards the surface. Breccias in the Rotokawa geothermal field were products of hydrothermal eruptions sourced from beneath Lake Rotokawa (Collar and Browne, 1985; Simpson et al., 2021; Montanaro et al., 2023).

A future iteration of the model can include changes that would address remaining negative gravity misfits such as adding structures to the northwest and southwest corners to either accommodate further drop in greywacke's elevation, adding shallower low-density bodies not intersected by drilling, or revisit the corrections applied to account for Lake Taupo. Remaining positive misfits can be addressed either by making greywacke shallower or by adding shallow high-density bodies above basement.

5. CONCLUSION

Application of 3D gravity forward and inverse modelling on Wairākei-Tauhara-Rotokawa geological model provided insights in refining areas unconstrained by drilling and could guide future drilling plans to better constrain parts of the geological model. The resulting final geological model showed that greywacke basement (or a lithology with similar density) is probably present on the western side beneath Wairākei geothermal field at >3000 m depth. The model also indicated the presence of a low-density vertical zone through the Rotokawa-Reporoa Andesite and underlying greywacke. The low-density zone could represent an area of concentrated intense hydrothermal alteration and possibly a buried hydrothermal breccia vent focusing fluid flow and manifesting on the surface as Lake Rotokawa.

Future refinements to the geological model could include other geophysical datasets such as magnetic data, which are sensitive to crystalline igneous rocks such as lavas or intrusions.

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