GRAVITY MODELLING OF REPOROA BASIN, EASTERN TAUPO VOLCANIC ZONE (TVZ), NEW ZEALAND

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ABSTRACT

Gravity data over the Reporoa Basin are interpreted using a new approach of three-dimensional (3D) modelling currently being developed by the author. With the help of upward continuation technique, the gravity anomalies are separated into a series of spatial components assumed to be associated with different "depth slices". Each set of spatial components is used to interpret the lateral density variation of its associated depth slice. The modelling allows semiautomatic determination of subsurface density distribution in 3D.

The modelling output indicates that below 2km depth the surface of TVZ greywacke basement is difficult to resolve using gravity data because of the small (<<0.06 g/cc), but also variable *density contrast* between the greywacke and the volcanic infill. However, it also appears that deeper density variation within the TVZ basement may be detected using this modelling approach.

The gravity interpretation shows that the Reporoa geothermal field is located close to the northwestern edge of a sub-circular low-density structure of the Reporoa Caldera. The caldera structure extends down to about 500m depth. A similar shallow circular low density structure occurs about 12 km SW, immediately west of the Ohaaki geothermal field. Below 500 m depth the two merge into a single NE-SW elongated low density structure marking the Reporoa Basin down to about 1500 m depth.

The gravity modelling output also indicate that the Paeroa Range west of Reporoa Basin is associated with dense volcanic rocks extending down to about 800 m depth. This block of dense rocks follows the western/north-western edge of the Reporoa Basin.

The gravity interpretation approach used in this study can be applied to other studies geothermal areas in complex volcanic setting and will help to reduce the bias often needed to be introduced during a more conventional forward modelling.

1. INTRODUCTION

Reporoa Basin is located near the eastern margin of the Taupo Volcanic Zone, a region of extensional volcano-tectonic depression in the Central North Island of New Zealand (Figure 1). The boundary of the Reporoa Basin in Figure 1 was mainly delineated from topography. This topographic basin is situated between the topographic ridge of Paeroa Range in the northwest and the Kaingaroa Plateau in the southeast.

Figure 2 shows a simplified geology of the study area showing the surface extents of two extensive Quaternary welded ignimbrites (the ~350 ka Whakamaru Group and the ~230 ka Kaingaroa Formation) and extruded lavas (rhyolite and dacite). The areas between these exposures are occupied by ignimbrite and pyroclastic formations of smaller extents and some younger surficial deposits (tephra and alluvium).

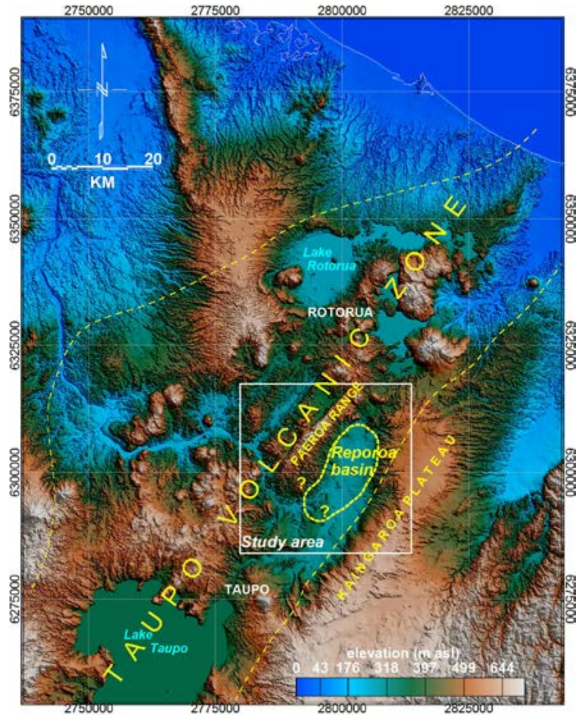

Figure 1: Location map of the study area in the Taupo Volcanic Zone, Central North Island, New Zealand. Coordinates are in NZ Map Grid (metres).

Basement rocks beneath the study area consist primarily of Mesozoic meta-sediments, termed greywacke (Wood et al., 2001), that have been covered by up to 3 km of the Quaternary deposits (Leonard et al., 2010).

The first regional 3D gravity modelling of basement depths across the whole TVZ was carried out by Rogan (1982). More recently the model was refined by Soengkono (2011). Both modelling works were carried out assuming a constant *density contrast* between the greywacke basement and the Quaternary volcanic infill. The model gives an overall perspective of the TVZ basement structures. However, the assumption of constant *density contrast* is not likely to be valid (Soengkono, 2011). Density data from geothermal drillhole cores clearly show that the density of the volcanic infill increases with depth (Stratford and Stern, 2008) and at depths >2,000m it becomes very close to the density of the greywacke basement.

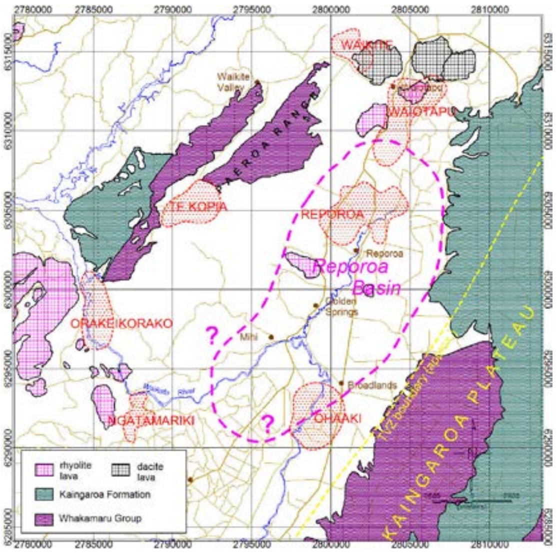

Figure 2: Simplified geology of the study area. Red dotted lines show extents of geothermal fields as indicated by Schlumberger resistivity data.

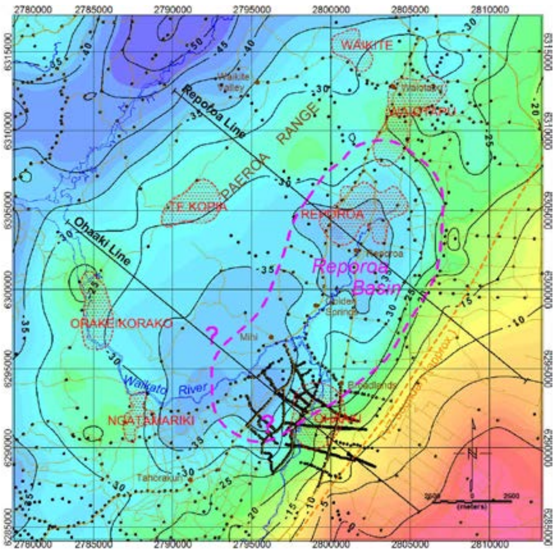

Figure 3: Residual Bouguer anomalies over the study area. Contour values are in mgals. Measurement sites are shown by black dots.

This study is partial to an attempt by the author to address the problem of gravity forward modeling caused by the inhomogeneity of the TVZ volcanic infill. Instead of the need to assign a certain density value(s) to the TVZ volcanic infill, the new modeling approach used in this study allows a semiautomatic determination of subsurface density distribution in 3D.

2. GRAVITY DATA

A total of 1323 gravity measurement sites are available on GNS gravity database over the study area. A map of residual Bouguer anomalies is presented in Figure 3. The residual anomalies were obtained by subtraction of a regional field defined using values of Bouguer gravity anomaly over exposed greywacke basement outside the TVZ (Stern, 1979).

The residual Bouguer anomalies in Figure 3 reflect mainly the gravitational effects of TVZ volcanic infill. However, these residual anomalies would also contain effects of any variation in the density of concealed basement with respect to the density of the exposed greywacke outside TVZ.

3. NEW APPROACH IN 3D GRAVITY MODELLING

The new approach of three-dimensional (3D) gravity modelling currently being developed by the author uses upward continuation transformation (Henderson and Zietz, 1949) to separate observed anomalies into a series of spatial components associated with different “depth slices” of density. Upward continuation transforms gravity data measured on one surface (the ground) to some higher surface. This transformation can be seen as a very-smooth (and stable) low pass filter that attenuates short wavelength anomalies relative to their longer wavelength counterparts (Dobrin and Savit, 1988). Upward continued data are associated with deeper-seated sources of the anomalies (Keary and Brooks, 1993). In this study, the upward continuation transformations were conducted using the upward continuation module of the *Oasis montaj* software (Geosoft).

Table 1 lists sixteen depth slice layers used in this modelling, together with their associated upward continuation levels (UPC-1 and UPC-2) and the depths to the top (Z-Top), bottom (Z-Bot) and middle (Z-Mid) of each layer. The correlation between UPC-1, UPC-2 and Z-Top, Z-Bot was resolved by some trial and error approach, aimed to obtain results which geologically *make sense*. Such a trial and error resolve is the largest source of bias in this modelling approach. In the data in Table 1, the depths selected are roughly equal to one fifth of upward continuation levels.

Table 1: Density layers used for the 3D semiautomatic inversion of gravity data, the associated upward continuation levels (UPC-1 and UPC-2), and the depths to the top (Z-Top), bottom (Z-Bot) and middle (Z-Mid) of each layer.

Layer#	UPC-1 (m)	UPC-2 (m)	Z-Top (m)	Z-Bot (m)	Z-Mid (m)
01	60	460	12	92	52
02	460	960	92	192	142
03	960	1590	192	318	255
04	1590	2370	318	474	396
05	2370	3340	474	668	571
06	3340	4560	668	912	790
07	4560	6090	912	1218	1065
08	6090	8000	1218	1600	1409
09	8000	10380	1600	2076	1838
10	10380	13360	2076	2672	2374
11	13360	17090	2672	3418	3045
12	17090	21740	3418	4348	3883
13	21740	27560	4348	5512	4930
14	27560	34840	5512	6968	6240
16	34840	43940	6968	8788	7878

For this preliminary inversion of gravity data, the observed residual anomalies (Figure 3) were gridded at 1,000 m grid size. The spatial components of the observed anomalies for each layer (depth slice) were obtained by subtracting corresponding UPC-2 output from UPC-1 output.

Figure 4 shows an example of the modelling process. The spatial component of observed residual anomalies for Layer #06 was obtained from upward continuation output of residual Bouguer anomalies to 3340 m level (UPC-1 in Table 1) subtracted by upward continuation output of the same data to 4560 m level (UPC-2 in Table 1). This spatial component was used to invert the density variation of Layer #06 at 1000m grid size, using the computational technique of Barnett (1976) to compute the gravitational effect of 1,000 m size vertical prism with variable top and bottom corners.

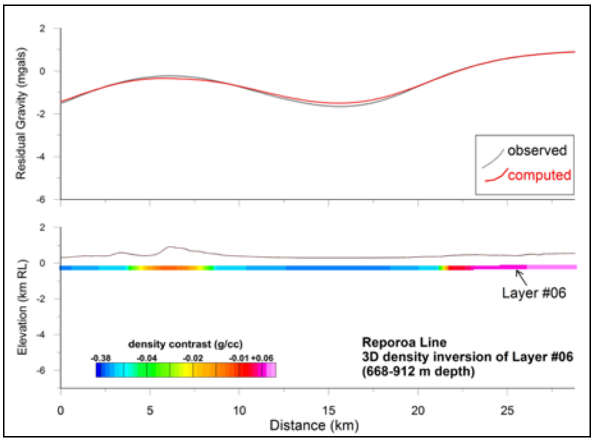

Figure 4: Example of 3D inversion process of Layer #06 (668 - 912 m depth; see Table 1) along Reporoa Line (Figure 3).

The same process was carried out for all sixteen layers listed in Table 1, to obtain full 3D inverted density variation over the whole study area. The computation is rather tedious and slow, as at current development stage of this 3D inversion approach, each layer has to be processed individually.

In relation to how the regional field was defined by Stern (1979), the inverted density values obtained by this modelling are in term of *density contrasts* with respect to average density of basement rocks where they are exposed outside TVZ (equal to 2.67 g/cc).

The rather large grid size (1,000m) was selected mainly to minimise computational time. It does limit the resolution of the inverted density variation. Any structure less than 1,000 m wide would not be resolved accurately by the modelling output. However, reducing grid size by half would considerably increase the computational time, by a factor of power two (^2).

The resolution of output is also limited by the number and the distribution of the gravity measurement sites within the study area. For the whole study area shown in Figure 3, the smallest grid size would be about 250 m.

4. 3D GRAVITY MODEL OF REPOROA BASIN AREA

Full modelling cross sections along the Reporoa and Ohaaki Lines (Figure 3) are presented in Figures 5 and 6, respectively.

The result along the Ohaaki Line (Figure 6) shows that the inverted density distribution is compatible with depth of basement given by geothermal drillhole data at Ohaaki field. The result also indicates that the basement surface is associated with a *density contrast* of about -0.065 g/cc for depths between 750 and 2,500 m. For depths greater than 2,500 m the *density contrast* between basement and volcanic infill is likely to become smaller than |-0.06| g/cc, which makes it difficult to resolve the basement depths using gravity data.

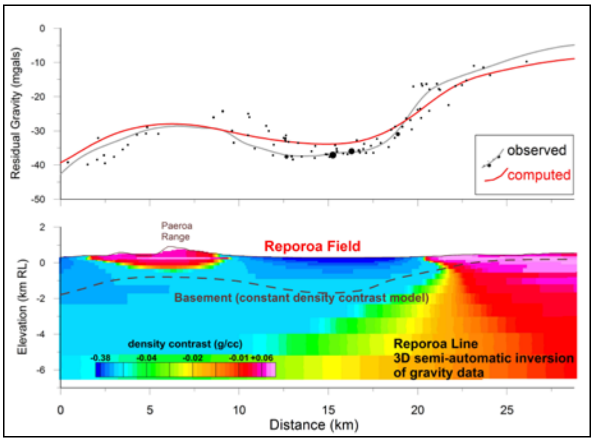

Figure 5: Modelling cross section along Reporoa line (Figure 3).

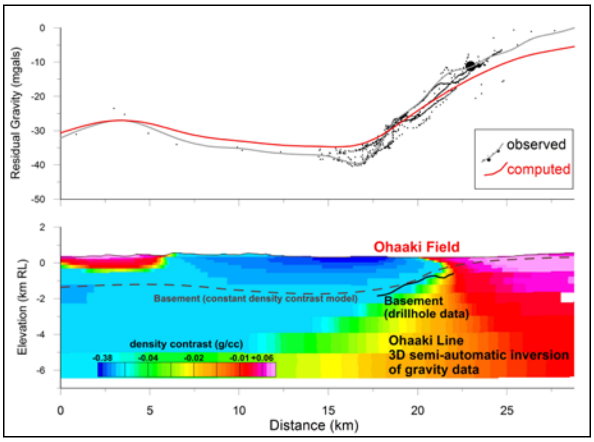

Figure 6: Modelling cross section along Ohaaki line (Figure 3).

An interesting feature shown in Figures 5 and 6 is that the density below 4 km depths (arguably too deep for the TVZ Quaternary volcanic infill) reduces towards the central axis of TVZ (towards the left direction in Figures 5 and 6). Tests of the modelling technique carried out using several different sets of upward continuation levels and depth slices showed that this phenomenon is unlikely to be an artefact of the modelling procedure.

This lowering density of basement rocks could be associated to regional fracturing caused by the extension of TVZ. Across the so-called Taupo Fault Belt to the northwest of the Paeroa Range, an extension rate of 6.4 mm/yr (at 6 to 10 km depth) during the last 50,000 years has been documented (Villamor and Berryman, 2001). Geodetic surveys have also indicate an extension rate of ~12 mm/yr across the Reporoa Basin (Wallace et al., 2004).

At shallower depths, the modelling results in Figures 5 and 6 show that the Reporoa Basin can be defined by *density contrast* value of about -0.2 g/cc (equivalent to density of 2.47 g/cc). Hence, the densities of infilling volcanic rocks of the Reporoa Basin are ≤ 2.47 g/cc (within 1,000 m resolution).

A comparison between the observed residual Bouguer anomalies and the computed effects of model over the whole study area is presented in Figure 7. Overall matching between computed and observed data is acceptable, but it could still be improved by finding out a better correlation between UPC-1 and UPC-2 to top and bottom of modelling layers (depth slices) than that shown in Table 1. Such a better correlation would improve the accuracy of the inverted density variation output.

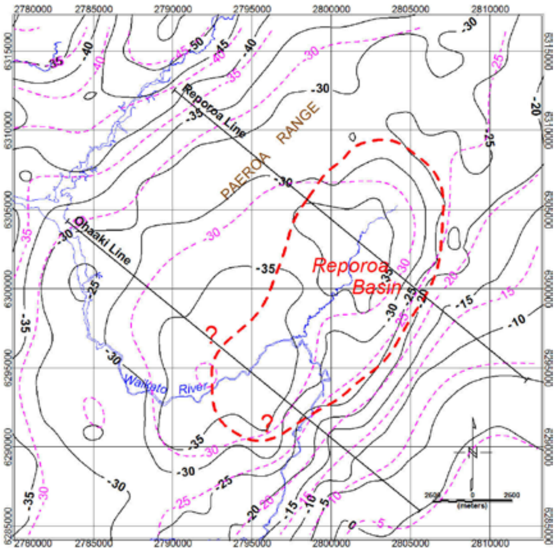

Figure 7: Comparison between observed residual Bouguer anomalies (black, solid contour lines) and computed anomalies of model (purple, dashed contour lines). Contour values are in mgals.

Slices of *density contrasts* at 400 m, 800 m and 2400 m depths are presented in Figures 8, 9 and 10, respectively. These results show a strong correlation between high density zones down to about 800 m depth and the extents of Whakamaru Group and Kaingaroa Formation. The Paeroa Range (formed by Whakamaru Group Ignimbrites) sits above the high density zone to the west/northeast of the Reporoa Basin (see also Figure 5).

The correlation between high density zones and the surface exposures of Whakamaru Group and Kaingaroa Formation disappears at below 800 m depth. The high density zone beneath the Kaingaroa Plateau shown in Figure 10 represents basement rocks.

The result in Figure 8 shows that the Reporoa Basin is slightly wider than shown by topography. However, the west/northwest extension of the basin is still rather poorly defined because of poor coverage of gravity measurement sites.

The results in Figure 8 also indicate two sub-basins within the greater Reporoa Basin. The north-eastern sub-basin matches the Reporoa Caldera. The south-western sub-basin (named Mihi Volcanic Depression) does not associate with any currently mapped caldera structure.

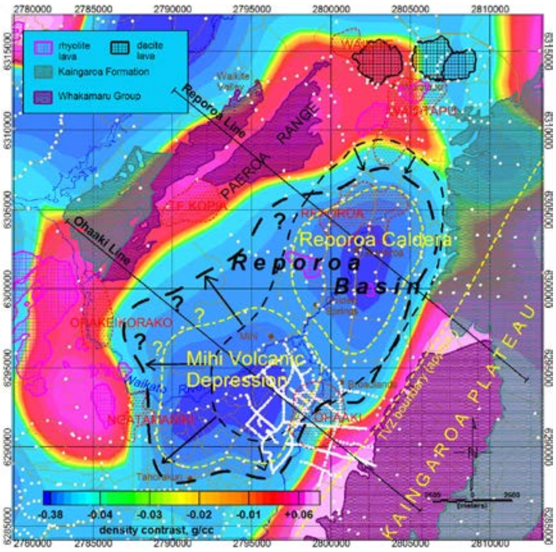

Figure 8: *Density contrasts* slice at 400 m depth. Gravity measurement sites are shown by white dots.

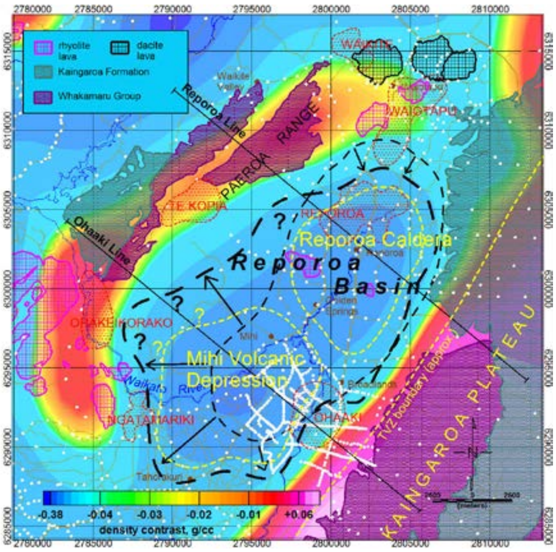

Figure 9: *Density contrasts* slice at 800 m depth. Gravity measurement sites are shown by white dots.

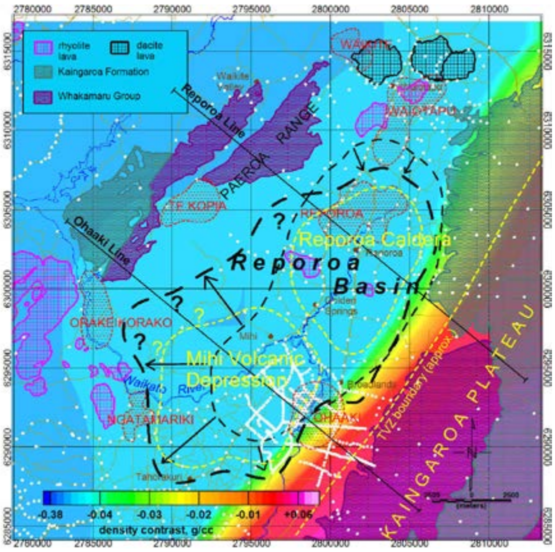

Figure 10: *Density contrasts* slice at 2,400 m depth. Gravity measurement sites are shown by white dots.

Below 500 m depth the Reporoa Caldera and the Mihi Volcanic Depression merge into the greater Reporoa basin which extend down to about 1,500 m depth.

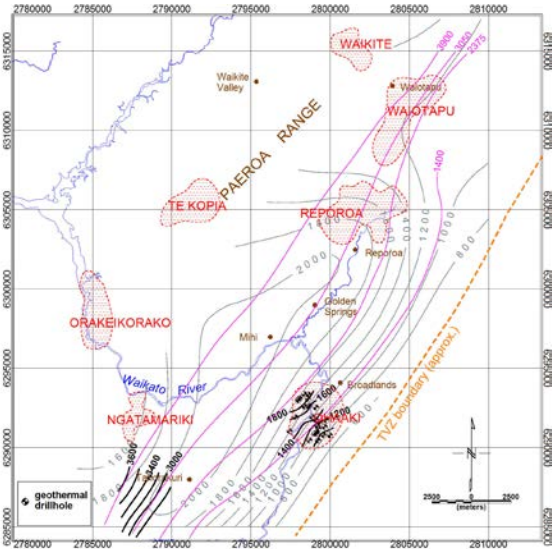

Figure 11: Comparison between greywacke basement depths (metres) suggested by the 3D inverted density (purple contour lines) and those indicated by geothermal drillholes (black contour lines) and from a previous 3D forward gravity interpretation assuming a constant density contrast (grey contour lines).

Figure 11 shows a comparison between the greywacke basement inferred from the 3D density inversion output (represented by *density contrast* value of -0.065 g/cc) and those defined by geothermal drillholes at Ohaaki and southeast of Ngatamariki, and suggested by previous forward modelling assuming a constant *density contrast* of -0.47 g/cc (Soengkono, 2011). The results in Figure 11 show that over the Ohaaki field, the three sets of basement depth are well matching to each other. The basement depths inverted in this study (purple lines) show a slightly better match to the drillhole data.

However, over the area to the southeast of the Ngatamariki field, the match between the previous forward modelling (grey lines) and the drillhole data (black lines) is very poor (showing discrepancy of more than 1,000 m). The basement depths inverted from this study (purple lines) show a much better match to the drillhole data, with less than 200m discrepancy.

5. DISCUSSION AND SUMMARY

This paper presents result from a new approach of 3D modelling that allows semiautomatic inversion of density from distribution of gravity anomalies. Further improvements are still needed, particularly in finding out a better way to pick appropriate upward continuation levels and to correlate such levels with the depths of the density slices. However, a trial run of the modelling approach over the Reporoa Basin has produced a good result.

Figure 12 shows the broad volcanic geological structures of the study area as suggested by the gravity modeling output.

The gravity inversion shows that the Reporoa Basin is slightly wider than that shown by topography. Two sub-basins occur inside the Reporoa Basin. The one in the northeast is associated with the Reporoa Caldera. No caldera structure has been mapped across the Mihi Volcanic depression in the southeast.

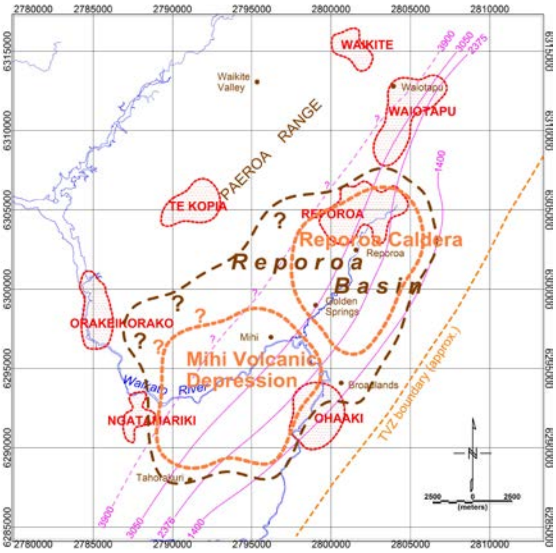

Figure 12: Broad geological structures of the study area as suggested by the result of the 3D semiautomatic inversion of gravity data. Purple contour lines are depths to basement corresponding to a *density contrast* of -0.065 g/cc.

There appears to be relationship between the caldera / volcanic depression and three of geothermal fields in the study area. The Reporoa geothermal field is located inside the Reporoa Caldera and close to its northwestern edge. The Ohaaki and Ngatamariki fields are located outside the Mihi Volcanic depression, but also very close to its edge. On a slightly larger scale, the Ohaaki, Ngatamariki, Orakeikorako, Te Kopia (?) and Waiotapu fields seem to be associated with the edge of the Reporoa Basin.

The gravity modelling output also indicates that the Paeroa Range is associated with dense volcanic rocks extending down to about 800 m depth. This block of dense rocks at shallow depth (which is closely associated with surface exposures of Whakamaru Group and Kaingaroa Formation) follows the western / north-western edge of the Reporoa Basin.

There is indication that the density of basement rocks is slightly reduced beneath the TVZ. If this is true, it could suggest the presence of regional basement fractures associated with the extension of the TVZ.

The gravity interpretation approach used in this study can be applied to studies of other geothermal areas in complex volcanic setting and will help to reduce the bias often needed to be introduced during a more conventional forward modelling. Higher resolution of output can be easily achieved over any smaller area with denser distribution of gravity measurement sites.

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