DEEP INTERPRETATION OF GRAVITY AND AIRBORNE MAGNETIC DATA OF THE CENTRAL TAUPO VOLCANIC ZONE

S. Soengkono

GNS Science Wairakei, Private Bag 2000. Taupo 3352

s.soengkono@gns.cri.nz

ABSTRACT

The Taupo Volcanic Zone (TVZ) is a region of Quaternary volcanic and geothermal activity in the central North Island of New Zealand. The zone is oriented SW-NE, about 350 km long and 60 km wide. It is bounded by ranges of Mesozoic sediments in the northwest and by the Kaingaroa ignimbrite plateau followed by ranges of Mesozoic sediments in the southeast. The Mesozoic sediments consist mainly of dense and indurated sandstone, siltstone and conglomerate and have been grouped together as Torlesse greywacke. The greywacke was found at 1-3 km depths beneath the TVZ volcanic infill by geothermal wells at the Kawerau, Ngatamariki, Ohaaki-Broadlands, Rotokawa and Tauhara fields, but not by wells drilled over the geothermal fields at Wairakei (maximum depth 2km) and Mokai (maximum depth 2.6 km).

Gravity data are available over the whole TVZ from surveys carried out by the GNS Science (formerly DSIR) and the NZ universities since early 1950's. A regional airborne magnetic survey (1,500 m asl, 3.6 km flight-line spacing) was carried out over TVZ by the DSIR in 1952. It was followed by lower altitude surveys (800±100 m asl, about 1 km flight-line spacing) conducted by the Geothermal Institute (Auckland University) between 1983 and 1998 covering all main geothermal fields in the 100 km long central TVZ (between Taupo in the SW and Kawerau in the NE). Between mid-1980's and early 2000's mineral exploration companies also carried out localised but very detailed (60 m above ground, ≤300m line spacing) over various parts of the TVZ. The largest detailed survey was that carried out by Glass Earth NZ Ltd in 2006 which covered more than 50% of the central TVZ area.

This study presents preliminary result of new combined three-dimensional (3D) interpretation of the gravity and airborne magnetic data of the central TVZ in terms of the dense and non-magnetic Torlesse greywacke, less-dense and moderately-magnetic Quaternary volcanic infill, and deep seated magnetic bodies beneath the volcanic zone. It provides new insights into our understanding of deep (>3km depth) structure and permeability control of this fascinating volcanic and geothermal region.

1. INTRODUCTION

The Taupo Volcanic Zone (TVZ) is a region of Quaternary volcanic and geothermal activity in the central North Island of New Zealand. It is a SW-NE oriented Quaternary volcano-tectonic depression flanked by outcropping Mesozoic greywacke basement in the west-northwest and east-southeast (Figure 1).
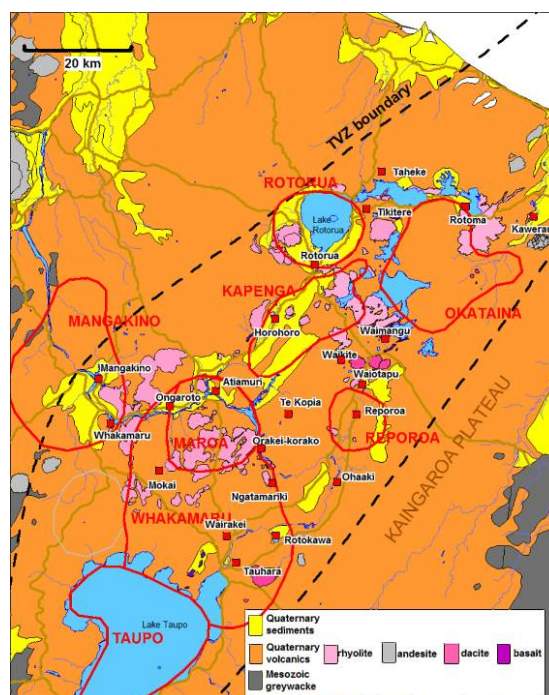

Figure 1: Simplified geology of the Taupo Volcanic Zone (TVZ).

Figure 1 also shows location of rhyolitic volcanic centres and associated calderas (thick red lines) defined by various geological mapping (Grindley, 1960; Healy et al, 1964; Wilson et al, 1984) and a previous three-dimensional (3-D) gravity interpretation (Rogan, 1982).

2. GEOPHYSICAL DATA

2.1 Gravity data

Almost all data from various gravity measurements that had been carried out over TVZ region since 1960s are available on the GNS gravity database. Figure 2 shows residual Bouguer anomalies over the region, obtained by a subtraction of a regional field defined using values of Bouguer gravity anomaly over outcropping greywacke basement outside the TVZ (Stern, 1979). The residual Bouguer anomalies are negative over TVZ, reflecting mainly the thickness of Quaternary volcanic infill over denser greywacke basement (Rogan, 1982).

2.2 Airborne magnetic data

Regional total force airborne magnetic anomalies from 1952 survey by DSIR (1500 m asl, EW flight lines at 3.6 km spacing) reported by Gerard and Lawrie (1955) are re-plotted in Figure 3. The figure also shows a deep magnetic model modified from Soengkono (1995) to be discussed later.
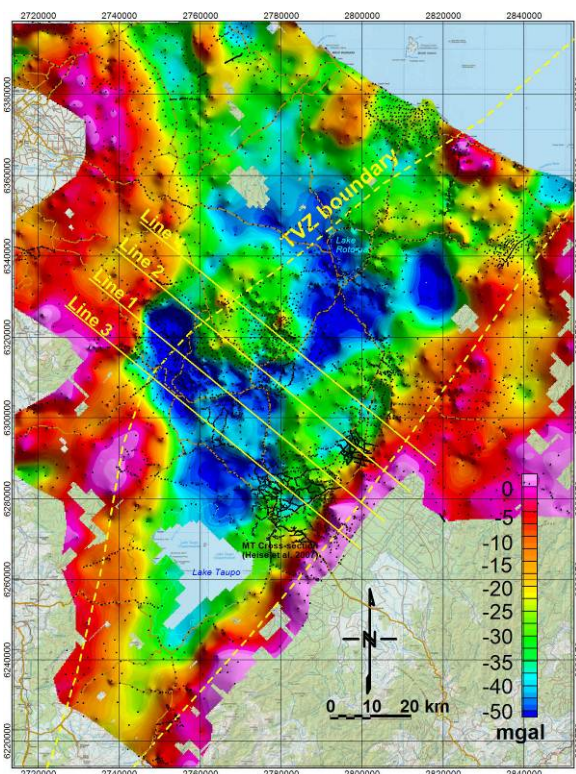
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Figure 2: Residual Bouguer anomalies of the Taupo Volcanic Zone (from GNS gravity database).
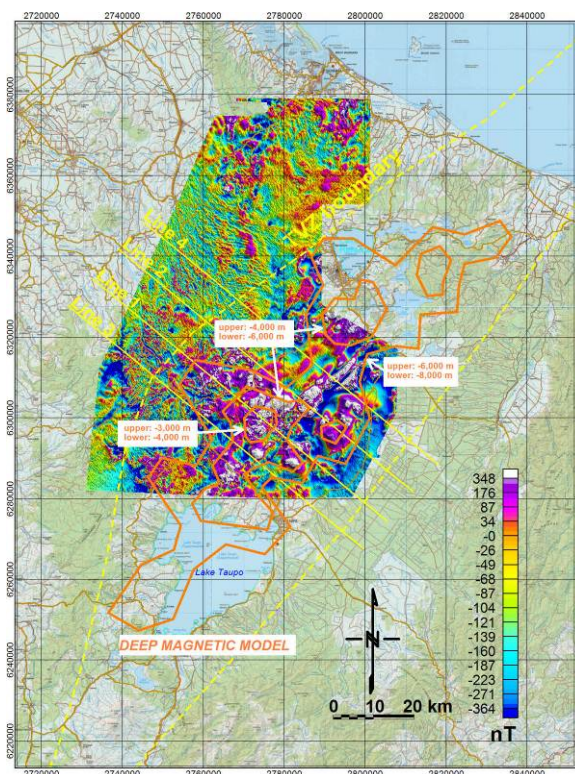

Figure 4: Detailed total force magnetic anomalies over central part of TVZ from 2006 airborne survey by Glass Earth NZ Ltd.
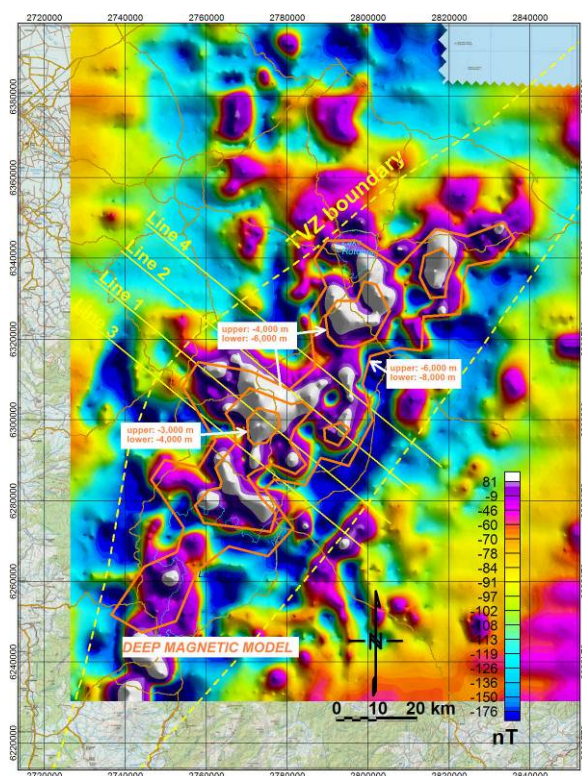

Figure 3: Regional total force magnetic anomalies from early 1950's DSIR airborne magnetic survey (Gerard and Lawrie, 1955).
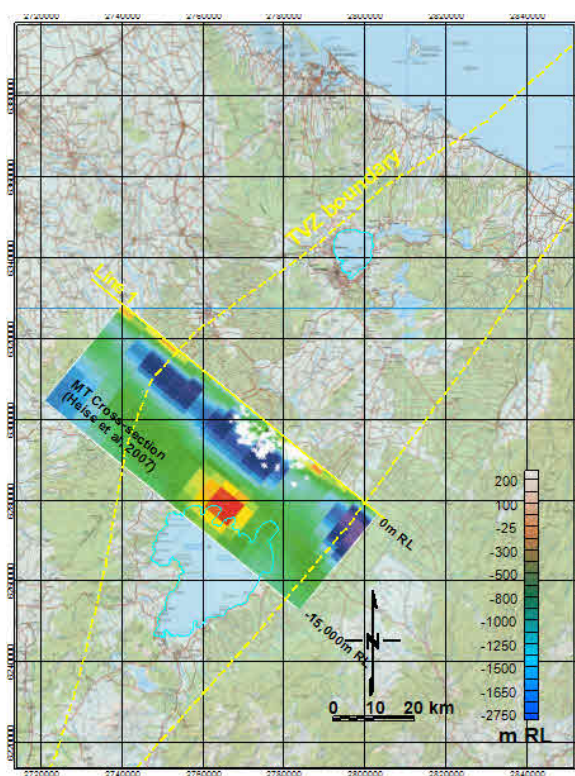

Figure 5: The results of the inversion of magnetotelluric (MT) measurements on a NW–SE line crossing the TVZ taken from Heise et al. (2007), plotted along the profile line location.

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Between 1983 and 1998 the Geothermal Institute (Auckland University) conducted series of airborne magnetic surveys at elevation of 800±100 m asl over a large part of TVZ. The data were mainly used for magnetic interpretations over some individual geothermal fields (eg. Hochstein and Soengkono, 1997). Most of the 800±100 m asl data have also been used together with the regional data in Figure 3 to construct deep magnetic model beneath TVZ (Soengkono, 1995), shown in Figures 3 and 4 (a modified version of the published model).

Figure 4 shows image plot of total force magnetic anomalies from more recent (2006) detailed survey by the gold exploration company Glass Earth NZ. The survey was carried out at 60 m above ground along E-W flight lines separated by 150 m spacing.

2.3 Magnetotelluric (MT) resistivity section

Extensive MT surveying have been carried out across the TVZ (Heise et al., 2007). In figure 5 part of the resistivity structure model derived from the MT measurements by Heise et al. (2007) is plotted along the profile line location. Conductive material occupies the upper part of the section reflecting accumulation of the TVZ Quaternary volcanic infill. A more resistive layer (typically 500–1500 m) beneath these surface conductors was interpreted by Heise et al. (2007) as the greywacke basement.

3. DEEP MODELLING OF THE GRAVITY AND AIRBORNE MAGNETIC DATA

3.1 Three-dimensional (3-D) gravity modelling

The 3-D gravity modeling in this study was carried out using the computational technique of Barnett (1976) in which an arbitrarily shaped 3-D model is represented by triangular facets over the entire surface of the body. This computational technique is more flexible than the earlier technique presented by Talwani and Ewing (1960) in which the arbitrarily shaped 3-D body is represented by a set of horizontal laminae of polygonal shape.

For this study, a computer code utilizing Barnett (1979) technique was written in Microsoft Visualbasic language to compute gravitational effects of 3-D "density layer" defined by rectangular grids of elevation at top and bottom. The grid size used for the TVZ modeling is 250 m. The top grid of the gravity model was fixed by the 250 m grid of digital topographic model (DTM) available from Land Information NZ. The bottom part of the model was adjusted until a good match was obtained between the computed effects of the model (assuming average densities of 2,200 kg/m^3 for volcanic infill and 2,670 kg/m^3 for the greywacke basement; a density contrast of -470 kg/m^3) and the observed residual gravity anomalies shown in Figure 2.

The 3-D gravity modeling section along Line 1 is presented in Figure 6. The upper figure shows plots of computed effects and the actual residual Bouguer anomalies at measurement sites within 5 km distances to the SW and NE of the profile line. Larger size of bubble plot indicates closer distance to profile line. The lower figure is the cross section of the best fit 3-D "density layer" of 2,200 kg/m^3 density overlying greywacke basement of 2,670 kg/m^3 density, superimposed on the MT resistivity inversion section taken from Heise et. al. (2007).

Figure 6 shows that the residual Bouguer anomalies over TVZ can be well matched by computed effects of Quaternary volcanic infill of variable thickness with a constant density of 2,200 kg/m^3 infilling the volcano tectonic depressions of the greywacke basement.

The whole 3-D gravity model of the TVZ greywacke basement surface (thickness of volcanic infill) based on this simplified 3-D modeling is shown in Figure 7. The location of rhyolitic volcanic centres and associated calderas area also shown (thick red lines). The very good match between gravity basement depressions and the volcanic centres of Okatania, Rotorua, Kapenga, Maroa, Reporoa and Mangakino shown by Figure 7 should not be surprising at all (and is not in any way reflecting a new finding of this work) as these centres were originally determined in part using the previous 3-D gravity modeling by Rogan (1982). However, the gravity model in Figure 7 does show the basement surface in more details, mainly because the modeling carried out in this study was more refined than that carried out by Rogan in 1982, but also because the new model incorporated some gravity measurements over TVZ carried out after Rogan's 1982 modeling.

There is a visible relationship between main faults drawn from geological mappings (solid yellow lines in Figure 6) and the basement model derived from the 3-D gravity interpretation.

The basement surface shown in Figure 7 is consistent (within ±200 m) with actual depth of greywacke basement from borehole data at Kawerau and Ohaaki. However, the match is not good at Rotokawa, Tauhara and Ngatamariki. Also, at Wairakei where the greywacke basement has not been penetrated by boreholes, the basement surface shown in Figure 6 is shallower than some deep Wairakei well. A refinement of the gravity model is obviously necessary to get a better match to more borehole data, however the model does give an overall perspective of the TVZ basement structures.
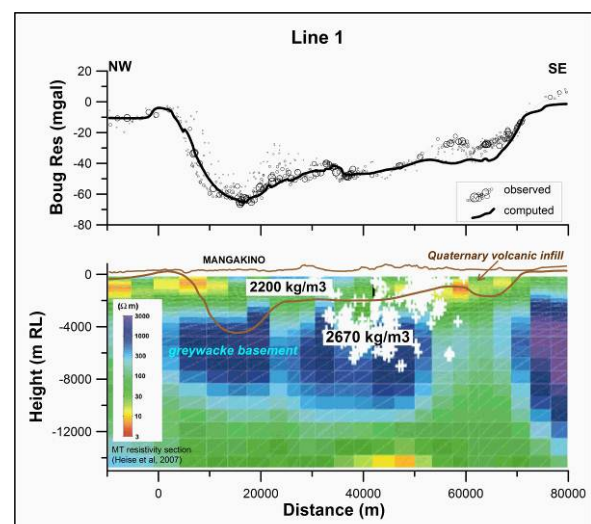

Figure 6: Three-dimensional (3-D) gravity modeling section along Line 1. The 3-D gravity model (lower figure) is superimposed on MT inversion section taken from Heise et. al. (2007).
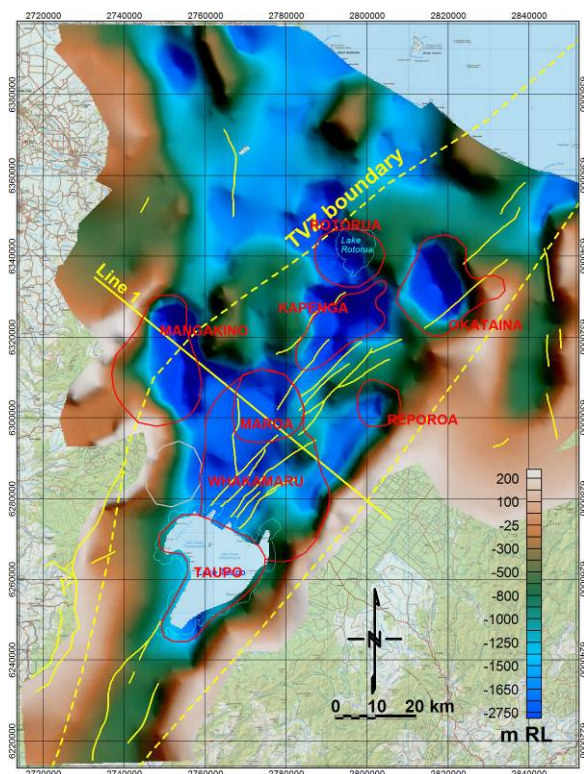
Figure 7: Greywacke basement surface beneath TVZ from a 3-D gravity model of 250 m horizontal grid, constructed by assuming a constant density contrast of -0.470 kg/m³ for the Quaternary volcanic infill.

3.2 Non-homogeneous density of Quaternary volcanic infill

Density measurements have been carried out by GNS (formerly DSIR) and other research institutions and universities for over more than 40 years on surface samples and borehole cores of the TVZ volcanic rocks and on samples of greywacke basement from various localities across the whole New Zealand region. The results documented at GNS show that the density of Mesozoic greywacke basement does not vary much from 2,670 kg/m³ value used in this study but the Quaternary TVZ volcanic rocks have noticeably variable densities due to their variations in lithology and porosity.

Interpretations of seismic refraction data (Robinson et al, 1981; Stern, 1986; Henrys and Hochstein, 1990; Stagpoole, 1994) indicate a general increase of the TVZ Quaternary rock density with depth. Hence, although the model shown in Figure 7 is geologically plausible and appears to be consistent with some geothermal borehole data, the assumption of constant density contrast of the volcanic infill is clearly not valid.

To check effects of variable density with depth, gravitational effects if the 3-D model in Figure 7 were recomputed using a simple density increase with depth approximated roughly from the available seismic refraction interpretations (Robinson et al, 1981; Stern, 1986; Henrys and Hochstein, 1990; Stagpoole, 1994) and the density data available at GNS database. The 3-D modelling profile along Line 1 from such re-computation is shown in Figure 8. It
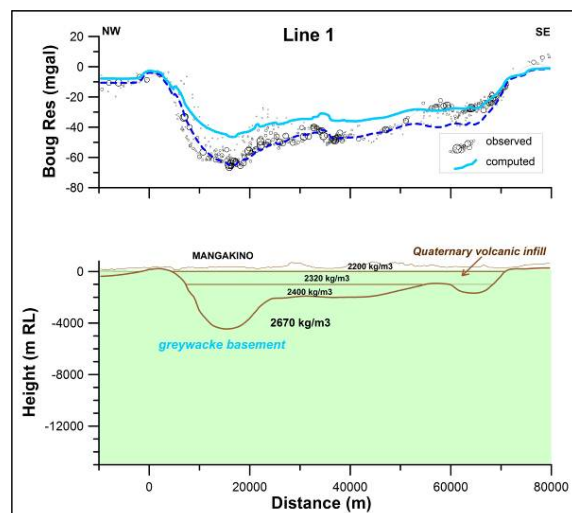

Figure 8: Three-dimensional (3-D) gravity modeling profile along Line 1 with the same model as shown in Figure 6 but with the Quaternary volcanic rocks having a simple increase of density with depth.

clearly shows that the computed gravitational effects of the Quaternary volcanic infill with density increases with depth become less than the observed residual anomalies. Two possible explanations of this are: (1) the basement is much deeper than that depicted in Figure 7, or (2) there are low density bodies beneath the basement surface.
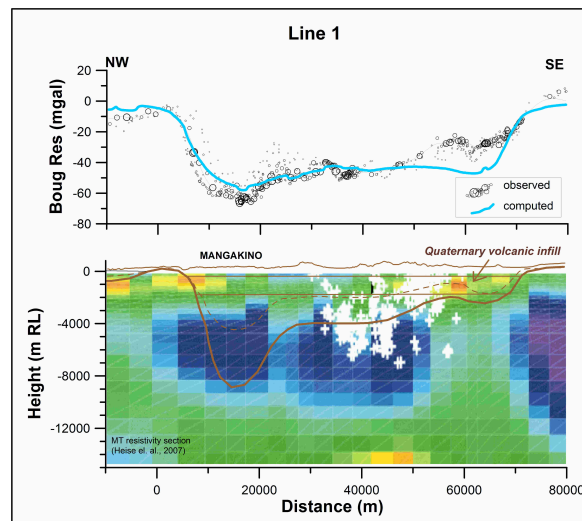

Figure 9: Three-dimensional (3-D) gravity modeling profile along Line 1 with a simple increase of density with depth for the Quaternary volcanic infill and deeper basement surface.

To check the plausibility of explanation (1), the depth of basement model in Figure 8 was increased until its computed effects fit the observed residual anomalies. The result (Figure 9) shows that increasing the basement depth did improve the matching computed effects, but the basement surface becomes unrealistically deep (averaging to more than 4000 m deep) with the Quaternary volcanic

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infill extending down to the region of deep resistive body indicated by the magnetotelluric data. Hence, the basement depth depicted in Figure 7 is probably about right, which means the explanation (2) becomes more likely, i.e there are low density bodies within the greywacke basement. The next question is: what are these masses?

3.3 Deep magnetic crustal masses beneath TVZ basement surface

The existence of deep magnetic crustal masses within the TVZ greywacke basement was suggested by Soengkono (1995).

Figure 10 shows 3-D magnetic modelling along Line 1 with a modified version of the model presented by Soengkono (1995). The magnetic effects of the interpreted deep magnetic body are shown in Figure 10 to have a reasonably good fit with the long wavelength components of the observed magnetic data at both 1500 m asl (Figure 3) and 60 m above ground (Figure 4). Figure 10 demonstrates the soundness of the deep magnetic model (see Figures 3 and 4 for lateral extent).
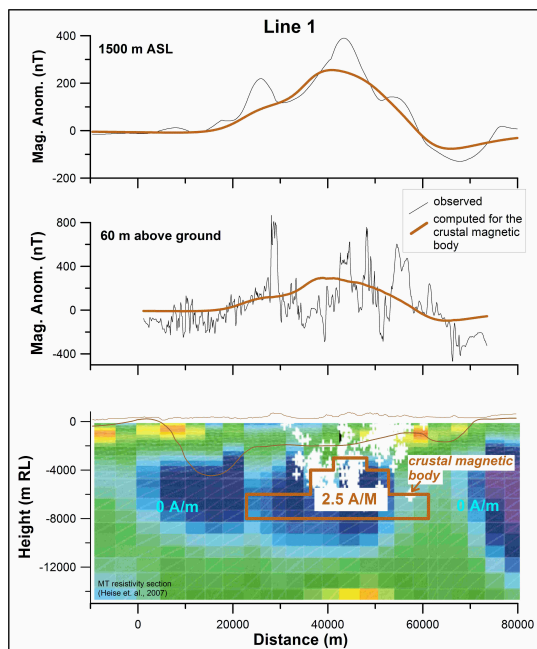

Figure 10: Three-dimensional (3-D) magnetic modeling profile along Line 1 of the model shown in Figures 3 and 4 at 1500 m asl (observed data in Figure 3) and 60 m above ground (observed data in Figure 4).

Soengkono (1995) suggested that such crustal magnetic masses represent intrusive bodies that had cooled down to below their Curie temperature. He further suggested on the basis of their average magnetization that their composition is likely to be rhyolitic, and hence they would be slightly less dense than the greywacke basement. A 2550 kg/m³ density body (slightly less dense that the greywacke basement) following the outline of the deep magnetic crustal masses were incorporated into the gravity modeling in Figure 11. Such incorporation visibly improves the matching between the computed and the observed anomalies except at Mangakino. No deep magnetic body is indicated beneath Mangakino by the magnetic data. It is

possible that the thickness of the western TVZ reversely magnetic volcanic rocks here (Soengkono et al, 1992) is substantial which would mask any positive anomalies from deeper sources, or that the densities of volcanic rocks infilling the Mangakino caldera are lower than that indicated in Figures 11 and 8.
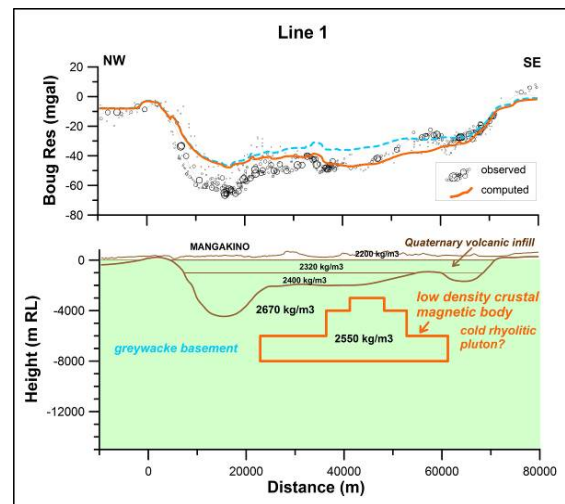

Figure 11: Three-dimensional (3-D) gravity modeling profile along Line 1 with the same Quaternary volcanic model as in Figure 8, and incorporating the deep crustal anomalous body shown in Figure 10 (assumed to have a density contrast of -0.120 kg/m³).
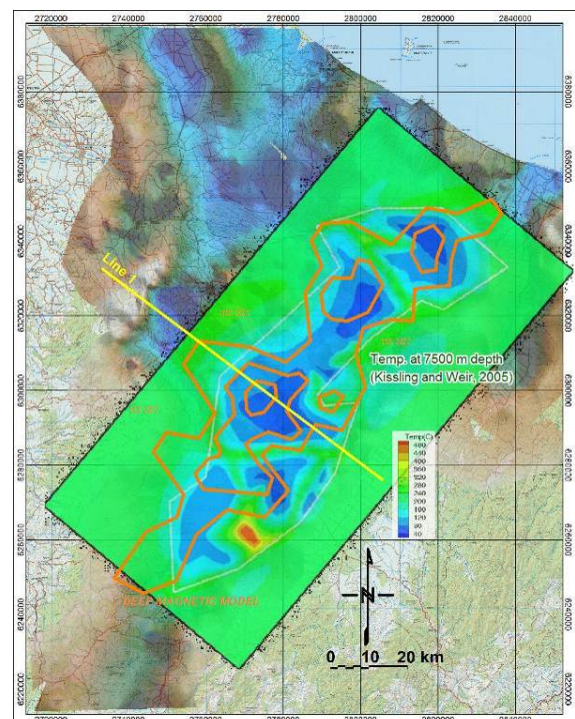

Figure 12: The extent of deep magnetic model (cold rhyolitic pluton) superimposed on a temperature map at 7.5 km depth given by TOUGH2 hydrological modeling of fluid/heat flow and rock mechanics of the TVZ (Kissling and Weir, 2005)

3.4 Comparison with deep temperature and permeability model

Kissling and Weir (2005) presented results of a TOUGH2 modelling of fluid/heat flow coupled with rock mechanics over the TVZ region. Their modelled temperature distribution at 7500 m depth is shown in Figure 12, superimposed by the outline of anomalous crustal masses interpreted from the magnetic data (Figures 3 and 4). It is noted that the temperatures shown in Kissling and Weir (2005)'s model are probably too low for 7500m depth (the dark blue colour indicates temperatures <80°). However, the consistency between the reduced temperature zones indicated by heat/fluid flow modelling and the cold sub-volcanic plutons interpreted from airborne magnetic data is remarkable. It suggests that the cold sub-volcanic body of plutons is somehow associated with permeable zones within or above it that allow deep down-flow of cold water.

4. CONCLUSION

A new 3-D basement gravity model of TVZ has been created. The model (Figure 7) is consistent with the previous model presented by Rogan (1982). However, with the more refined modelling technique used in this work, there are details of the basement structures in Figure 7 that are not clearly visible in the previous model presented by Rogan (1982).

A more significant result of this study is that when a more realistic density structure of the TVZ volcanic infill was used, the 3-D gravity modelling suggests the existence of low density masses beneath the basement surface. Such low density masses could represent the magnetic crustal masses indicated by regional 3-D interpretation of airborne magnetic data. If this true, it supports the suggestion by Soengkono (1995) that the magnetic crustal masses represent sub-volcanic plutons formed by accumulation of rhyolitic intrusions (hence, the relatively low density) that have cooled down to below their Curie temperature.

There is a remarkable consistency between the interpreted cold sub-volcanic plutons interpreted from the magnetic data (this study) and relatively low temperature zones given by TOUGH2 modelling of heat/fluid flow beneath the TVZ (Kissling and Weir, 2005).

ACKNOWLEDGEMENTS

REFERENCES
Barnett, C.T.: *Theoretical modeling of the magnetic and gravitational fields of an arbitrarily shaped three-dimensional body*. Geophysics 41 (6), pp 1353-1364 (1976).

Grindley, G.W.: *Taupo, Geological map of new Zealand, sheet 8, scale 1;250,00,* Department of Scientific and Industrial Research, Wellington, Wellington, New Zealand (1960).

Healy, J., Schofield, J. C., and Thompson, B.N.: *Rotorua, Geological map of new Zealand, sheet 5, scale 1;250,00,* Department of Scientific and Industrial Research, Wellington, New Zealand (1964).

Heise, W., Bibby, H.M., Caldwell, T.G., Bannister, S.C., Ogawa, T., Takakura, S.,Uchida, T.: *Melt distribution beneath a young continental rift: the Taupo Volcanic Zone, New Zealand*. Geophysical Research Letters 34, L14313, doi:10.1029/2007GL029629 (2007).

Henrys, S.A. and Hochstein, M.P.: *Geophysical structure of the Broadlands-Ohaaki geothermal field (New Zealand*. Geothermic 19 (2), pp. 129-150 (1990)

Hochstein, M.P. and Soengkono, S.: *Magnetic Anomalies Associated With High Temperature Reservoirs in the Taupo Volcanic Zone (New Zealand)*. Geothermics 26 (1), pp 1-24 (1997).

Kissling, W.M. and Weir, G.J.: *The spatial distribution of the geothermal fields in the Taupo Volcanic Zone, New Zealand*. Journal of Volcanology and Geothermal Research 145, pp 136-150 (2005).

Robinson, R., Smith, E.G.C. and Latter, J.H.: *Seismic studies of the crust under the hydrothermal areas of the Taupo Volcanic Zone, New Zealand*. Journal of Volcanology and Geothermal Research 9, pp. 253-267 (1981).

Rogan, A.M: *A geophysical study of the Taupo Volcanic Zone, New Zealand*. Journal of Geophysical Research 87, pp. 4073-4088 (1982).

Soengkono, S., Hochstein, M.P., Smith, I.E.M., Itaya, T.: *Geophysical Evidence for Widespread Reversely Magnetised Pyroclastics in the Western Taupo Volcanic Zone (New Zealand)*. New Zealand Journal of Geology and Geophysics 35, pp. 47-55 (1992).

Soengkono, S.: *A magnetic model for deep plutonic bodies beneath the central Taupo Volcanic Zone, North Island, New Zealand*. Journal of Volcanology and Geothermal Research 68, pp 193-207 (1995)

Stagpoole, V.M.: *Interpretation of refraction seismic and gravity data across the eastern margin of the Taupo Volcanic Zone,New Zealand*. Geothermics 23, pp 501-510 (1994).

Stern, T. A.: *Regional and residual gravity fields, central North Island, New Zealand*. New Zealand Journal of geology and geophysics 22, pp 479-485 (1979).

Stern, T,A.: *Geophysical studies of the upper crust within the Central Volcanic Region of New Zealand*. In: I.E.M. Smith (ED): Late Cenozoic volcanism in New Zealand. Royal Society of New Zealand Bulletin 23, pp. 93-111 (1986).

Talwani, M. and Ewing, M,: *Rapid computation of gravitational attraction of three-dimensioanl bodies of arbitrary shape*. Geophysics 25, pp 203-225 (1960)

Wilson, C.J.N., Rogan, A,M., Smith, I.E.M, Northey, D.J., Nairn, I.A.. and Houghton, B.F.: *Caldera volcanoes of the Taupo Volcanic Zone, New Zealand*. Journal of Geophysical Research 89, pp 8463-8484 (1984).

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