Proc. 12th New Zealand Geothermal Workshop 1990

GRAVITY SURVEY OF THE ROTOKAWA GEOTHERMAL FIELD

T.M. Hunt[1] C. Harms[2]

[1]D.S.I.R., Geology & Geophysics, Geothermal Research Centre, Private Bag, Taupo, New Zealand
[2]Geology Department, University of Gottingen, Federal Republic of Germany

ABSTRACT

Residual gravity anomalies near the field were split into two components. A first-order component (up to -370 μN/kg) associated with variations in the depth of basement as a result of vertical movements on the Kaingaroa Fault: and a second-order component (up to +100 μN/kg) associated mainly with lateral variations in the distribution of near surface (< 1 km depth) rhyolites.

Simple 3-D geophysical models suggest that rhyolites occur at depth over a wide area (including the field) which extends between Lake Rotokawa, Mt Kaimanawa, and Mt Whakapapataringa. The thickness of rhyolite predicted by the models is in good agreement with that found in drillholes RK1, 4, and 5; but much greater than found in RK6, but the reason for the discrepancy is not known.

The results show that near-surface rhyolites make a significant contribution to the gravity anomaly pattern in parts of the Central Volcanic Region and these anomalies cannot be interpreted solely in terms of variations of basement depth.

INTRODUCTION

Rotokawa is a small (< 30 km²) Geothermal Field, situated between Wairakei and Broadlands (Ohaaki) fields. The field is about 5 km north-west of the Kaingaroa Fault (Fig.1) This fault, or more strictly a fault zone several kilometres wide, is a major structural feature, and marks the eastern boundary of the Central Volcanic Region (CVR). The field lies in a thick sequence of volcanic cover rocks which overlies greywacke type basement rock similar to that found bordering the CVR. East of the fault are thin (< 250 m) ignimbrite sheets overlying greywacke. In the northern part of the area the surface geology is dominated by rhyolite lava flows from the domes of Oruahineawe, Kaimanawa, and a small unnamed dome lying between them. The flows are extensively surrounded, and in places overlain, by coarse rhyolite breccias.

At the time this study was made, six deep holes had been drilled within the field (Fig.1): RK1 and RK2 in 1966 to depths of 1200 and 880 m respectively, RK3 in 1977 to 910 m, RK4 and RK5 in 1984 to 2570 and 2783 m, and RK6 in 1985 to 2440 m. All the holes have maximum temperatures in excess of 285°C, with a highest maximum of 332°C in RK3, the greatest temperature measured in any geothermal drillhole in New Zealand.

Drillhole data suggest the geological sequence at Rotokawa is similar to that at Wairakei: a series of near-flat, lacustrine sediments, tuffs and ignimbrite sheets. interbedded with rhyolite flows, which overlie a thick (900 - 1200 m) unit of andesite flows. Only one drillhole (RK4) penetrated the andesite and encountered greywacke type basement rocks at a depth of 2200 m.

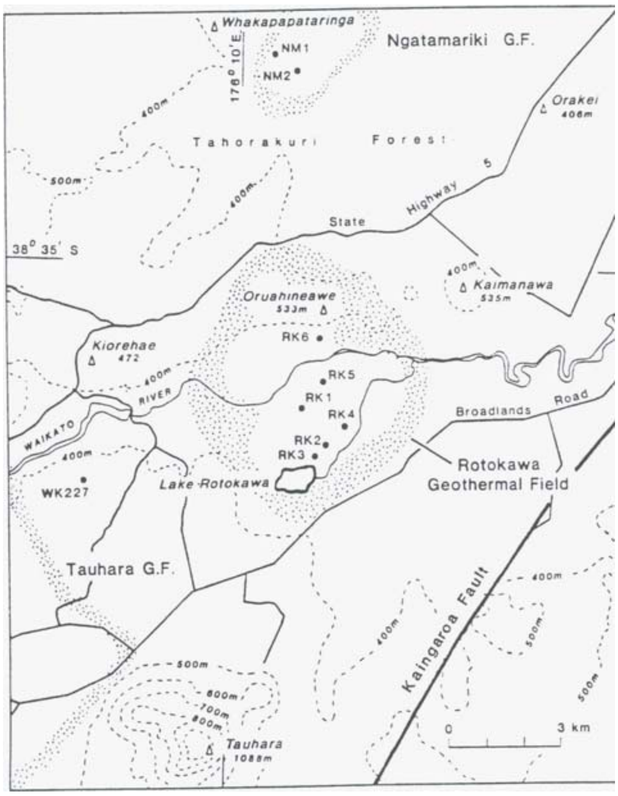

Fig. 1: Map showing the extent of Rotokawa Geothermal Field and the location of drillholes. The boundaries of the geothermal fields are shown by dotted areas and were determined from electrical resistivity measurements. Solid dots mark the positions of drillholes. The position of the Kaingaroa Fault is taken from Grindley (1961) and marks the south-eastern extent of basement displacement. Topographic contours are shown as broken lines.

GRAVITY MEASUREMENTS

Gravity measurements in the Rotokawa area were made in 1950-51 during exploration of the Wairakei Geothermal Power Scheme. Beck and Robertson (1955) constructed a residual anomaly map from these data which showed that steep gravity gradients occur near the Kaingaroa Fault, with localised gravity "highs" near the rhyolite domes of Oruahineawe, Kaimanawa, and Whakapapataringa, and gravity "lows" west of Lake Rotokawa. Robertson (1951) noted the gravity highs extending along the line between Oruahineawe and Kaimanawa, but considered them to be the result of basement uplift rather than the presence of dense igneous rocks because airborne magnetic measurements showed there were no large magnetic anomalies in the area. Modriniak and Studt (1959) and Rogan (1982) also interpreted the gravity pattern in the Rotokawa area purely in terms of the depth of the greywacke basement.

Detailed gravity studies since the early 1970's (Hochstein and Hunt 1970; Hochstein and Henrys, 1989) have shown that this simple interpretation is not always correct. Significant parts of the gravity anomalies mapped in the CVR may be due to local densification of the volcanic cover rocks associated with mineral deposition from upwelling geothermal fluids, or to variations in the distribution of rhyolitic and andesitic lava flows.

In addition to about 550 earlier gravity stations, a further 133 stations were made for this study. Bouguer gravity anomalies were calculated (or recalculated, in the case of the earlier data) in the standard manner described by Woodward (1982). The errors in the anomaly values is estimated to be ± 10 µN/kg (i.e. ± 1 mgal), however, at about half of the earlier gravity stations the elevation was determined by spirit levelling and at these places the error is probably ± 1 µN/kg. Six new measurements were made at or near (<200 m distant) to earlier stations in areas of low anomaly gradients; the largest difference in Bouguer anomaly value between the earlier and new stations is 4 µN/kg, and the mean difference is 2 µN/kg. The new measurements are therefore consistent with the earlier data.

Regional gravity anomalies, associated with variations in crustal thickness and other deep-seated (> 5 km depth) or extensive bodies, were taken from Stem (1979); these had been derived by fitting a low-order polynomial to the gravity data at 114 gravity stations situated on the greywacke rocks that crop out near the edges of the CVR Residual gravity anomalies in the Rotokawa area, obtained by subtraction of these regional anomalies from the Bouguer anomalies, are shown in Fig.2.

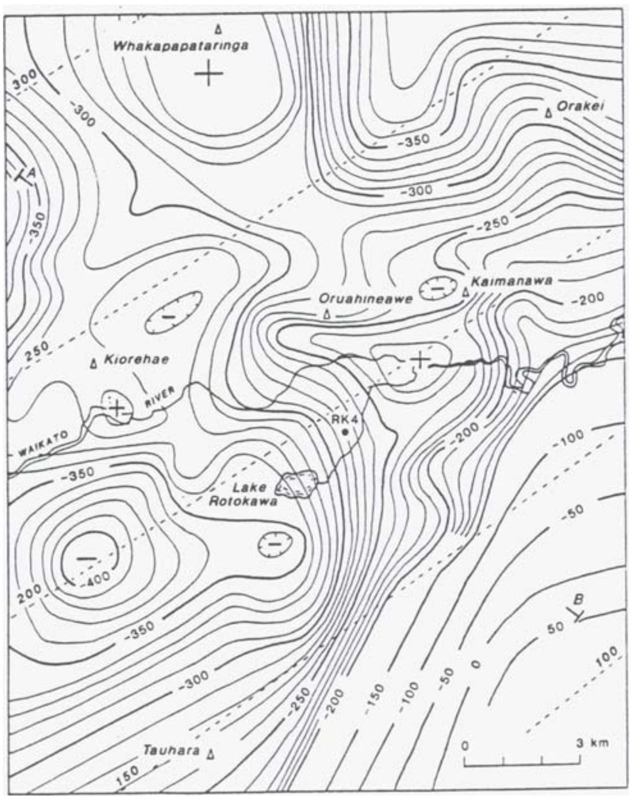

Fig. 2: Residual (solid lines) and regional (broken Lines) gravity anomalies (µN/kg) in the Rotokawa area. A-B marks the position of the profile shown in Fig. 4.

ROCK DENSITIES

Density measurements are available only for cores taken from holes RK4-6. A plot of wet density against depth (Fig.3) shows that, for depths less than about 1.5 km, the density values fall into two groups: rocks of the Haparangi Rhyolite Formation with densities of 2.09-2.44 Mg/m^3; and pumice, ignimbrite, tuffs, and lacustrine sediments having much lower densities, at the same depth. Below a depth of about 1.5 km, all the cores obtained are from the Rotokawa Andesite Formation, and have wet densities of 2.50-2.74 Mg/m^3. The mean wet density of these andesites is 2.60 (± 0.07) Mg/m^3. Several specimens which have relatively low density (<2.60 Mg/m^3) show strong brecciation, or are hydrothermally altered, and so the mean value obtained may be lower than that for unaltered rocks of this formation outside of the field. Two specimens from a core having a low (<10%) intensity of hydrothermal alteration have densities of 2.73 Mg/m^3. The density of the Rotokawa andesites outside the field may therefore be 2.65-2.70 Mg/m^3.

The density of the greywacke basement rock in RK4 has not been measured, nor does any greywacke crop out in the Rotokawa area. Greywacke encountered in drill-holes at Broadlands, 15 km to the north-east, has a density of 2.61 (± 0.09) Mg/m^3 (Hochstein and Hunt, 1970).

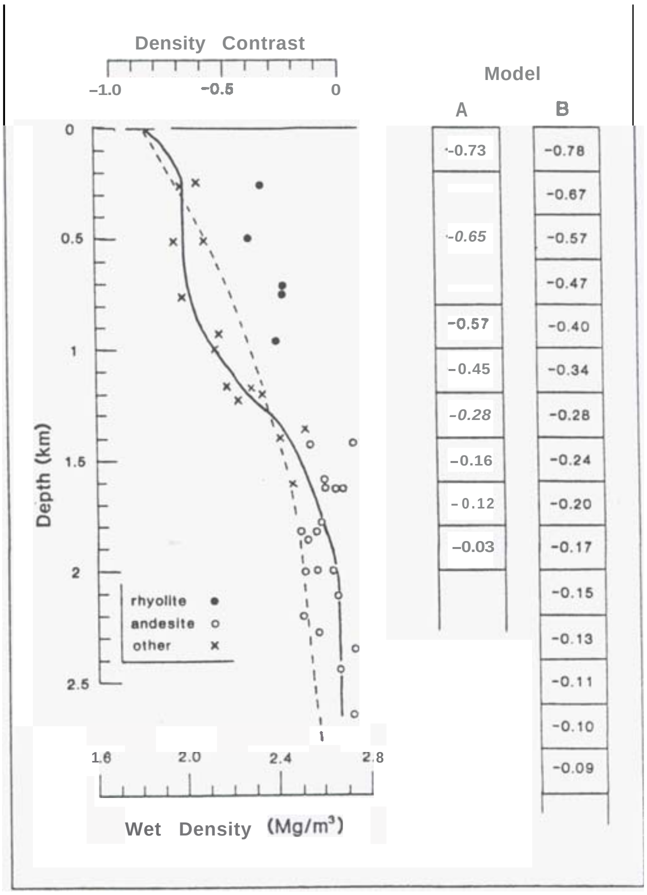

Fig. 3: Plot of density against depth for rocks from drillholes at Rotokawa, and the density/depth models used in the interpretation. The solid black line is the density/depth curve used in modelling the first order residual anomalies and is approximated by Model A. The broken line is the curve given by Stern (1982) for Wairakei and is approximated by Model B. Note the densities of the rhyolites are greater than for the other rocks, at the same depth.

RESIDUAL GRAVITY ANOMALIES

The residual anomalies (Fig. 2) show steep gravity gradients in the south-eastem part of the Rotokawa area which are linear, continuous, and roughly coincident with the Kaingaroa Fault. The anomalies in this part will therefore reflect mainly the relief of basement rocks as a result of vertical movement on the fault. Elsewhere in the area the residual anomalies are negative, with local maxima and minima that probably reflect density variations in the volcanic cover rocks.

The same approach to interpretation can be taken as that adopted by Hochstein and Hunt (1970) for Broadlands. Assuming that: the basement relief can be approximated by a simple geometrical model, density variations within the basement are negligible, and the effects of the thin (<250 m) volcanic cover rocks east of the Kaingaroa Fault can be ignored, then the residual gravity anomalies can be separated into two components:

(a) First order residual anomalies of relatively long wavelength, which reflect mainly changes in the basement depth.

(b) Second order residual anomalies of relatively short wavelength, which reflect mainly lateral density variations resulting from differences in the horizontal dismbution or thickness of rock units within the volcanic cover.

INTERPRETATION OF THE FIRST ORDER RESIDUAL ANOMALIES

Drillhole and gravity data at Broadlands are consistent with the "averaged basement surface" (greywacke) dipping at about 20° (± 5°) from the Kaingaroa Fault (Hochstein and Hunt, 1970). This value of 20° represents the progressive amount of step-wise vertical displacement of the basement surface by numerous sub-parallel faults in the fault zone. The only information available about the depth of basement rocks in the Rotokawa area is that greywacke occurs at 2200 m depth in RK4. Assuming that the greywacke dips uniformly from the surface at the fault to RK4, then the dip of this surface at Rotokawa is about 22°, a similar value to that for Broadlands.

To determine the first order residual anomalies, the basement surface at Rotokawa was approximated by a "2-d" model, with infinite extent parallel to the strike of the Kaingaroa Fault, in which the basement dips at 22° in a north-westerly direction. The effect of a slight curvature in the strike of the fault has been ignored. The variation of density with depth in the volcanic cover rocks was assumed to be that determined from the measurements on cores (Fig.3); in the model, the variation was approximated by horizontal layers of varying thickness and density contrast (Model A, Fig.3). Geological data from the drillholes at Rotokawa show that many of the rock units present are similar to those found at Wairakei, Ngatamariki and at Broadlands, and hence they extend over a wide area. The Haparangi Rhyolite and Rotokawa Andesite formations, however, are not continuous over the area and so these units were not taken into account in the density/depth model. In the model, the basement surface has been assumed not to extend deeper than 3 km, mainly because the residual anomalies appear to flatten out between -300 and -350 μN/kg along the western part of the profile line A-B (Fig.4). Errors associated with this assumption are likely to be small because the density contrast between the cover rocks and basement at this depth is small (<0.1 Mg/m^3; Fig.3).

The gravity effects of this model were computed (Talwani and Landisman, 1959), and are shown in Fig.4. For comparison the effects of a similar model in which the variation of density with depth is that given by Stern (1982) for the Wairakei area (Model B, Fig.3), are also shown.

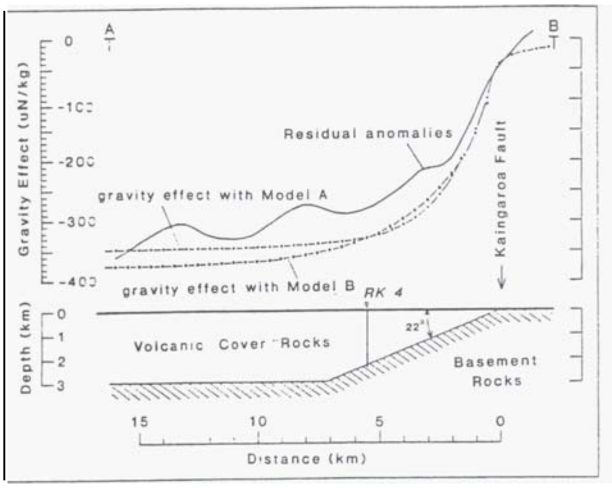

Fig. 4: Residual gravity anomaly profile across the Rotokawa area (solid line). The gravity effects of the variation in depth of the basement rocks (i.e. first order residual anomalies) are shown by broken lines; in Model A the densityidepth relation for the cover rock; is that for Rotokawa and is based on data from drillholes, in Model B the relation is that for Wairakei given by Stern (1982).

INTERPRETATION OF THE SECOND ORDER RESIDUAL ANOMALIES

A map of the second order residual anomalies (Fig.5) was obtained by subtracting the first order residuals (using densitydepth Model A) from the residual anomalies. The main feature of this map is a group of three positive gravity anomalies of up to 120 μN/kg amplitude, which occur near Oruahineawe and Kaimanawa. The westernmost of these anomalies, centred near Oruahineawe, lies mainly within the resistivity boundary of the Rotokawa Geothermal Field; the other two anomalies lie outside the field. Other positive anomalies occur near Whakapapataringa (80 μN/kg amplitude) and Tauhara (60 μN/kg), on the edges of the map. A negative anomaly of about 40 μN/kg amplitude occurs about 5 km south of Kiorehae, and extends eastwards towards the Kaingaroa Fault.

The splitting of the Bouguer anomalies into three components: regional, first order residual, and second order residual anomalies, was a subjective process. The least reliable part of this is the separation of the first and second order residual anomalies, and depends largely on two assumptions:

(i) the density-depth relationship,
(ii) the angle of dip of the "averaged basement surface".

The density-depth relationship was obtained from 32 measurements of which only 14 are for the critical depth range of 0-1.5 km, and is clearly the "weakest link". The angle of dip taken (22°) is close to that at Broadlands (20°) and is therefore probably fairly reliable.

To estimate the effect of uncertainties in the separation of the first and second order residual anomalies, another first order residual was constructed using the density-depth relationship for the Wairakei area (Model B, Fig. 3). The corresponding second order residual, derived using this first order residual, is shown in Fig. 6. A comparison of the two second order residual anomalies (Figs. 5 and 6) shows that the main effect of the different density-depth relationship is to alter the amplitude of the local anomalies, particularly in the north-western part of the Rotokawa area, but not to affect significantly their location.

Origin of the Anomalies

The rhyolites (Rotokawa Rhyolite Formation) are generally 0.30 - 0.45 Mg/m^3 more dense than the other rocks (tuffs, ignimbrites, breccias, etc) at corresponding depths (Fig.3), and the mean density contrast between the rhyolites and the other rocks is +0.36 (± 0.07) Mg/m^3. The mean density contrast between andesites (Rotokawa Andesite Formation) and the density-depth relation is +0.01 (± 0.11) Mg/m^3, and so the andesites will have little gravity expression in the second order residual anomalies. At Broadlands there is a significant increase in density with increase in rank of hydrothermal alteration, and there is a density contrast of up to 0.4 Mg/m^3 between some hydrothermally altered and unaltered rocks of the same unit (Hochstein and Hunt, 1970). This contrast is of similar magnitude to that of the rhyolites at Rotokawa but there is insufficient data available to determine if these effects also occur at Rotokawa. At Broadlands, densification occurs mainly in the inner parts of the field, and the associated gravity anomalies are confined to the field. It is likely that this effect, if present at Rotokawa, will also be confined to the field; however, at Rotokawa most of the positive anomalies are located outside the field, therefore the effects of densification are likely to have little effect on the interpretation presented here. The simplest explanation for the positive residual gravity anomalies in the Rotokawa area is that they are dominantly associated with rhyolite bodies.

The pattern of positive second order residual gravity anomalies, taken in conjunction with the outcrops of rhyolite on Oruahineawe and Kaimanawa, and the presence of rhyolites in all the holes at Rotokawa, suggests that a rhyolite body, or more probably a collection of such bodies, extends for a radius of about 6 km around Kaimanawa. Close inspection of the anomalies shows that the maximum anomaly values do not coincide with the surface outcrops of rhyolite on Oruahineawe and Kaimanawa, but are displaced to the south. This displacement results mainly from the use of a standard density of 2.67 Mg/m^3 for topography in reduction of the Bouguer anomalies, rather than a true density of about 2.3 Mg/m^3.

Positive residual gravity anomalies, outcrops of rhyolite on Whakapapataringa, and the presence of rhyolite in drillholes at Ngatamariki (Fig.1), suggest that a rhyolite body of similar extent also occurs near Whakapapataringa. Positive anomalies also occur near Mt Tauhara but are probably associated with dacite flows from this volcanic cone.

The negative residual gravity anomalies south of Kiorehae and Lake Rotokawa probably reflect the presence of low density tuffs and pyroclastic rocks and suggest that the rhyolites centred near Kaimanawa are either thin, or absent, south and south-west of the Lake Rotokawa. Similar negative residual gravity anomalies between Whakapapataringa and Orakei suggest that the rhyolites are probably thin or absent in this vicinity.

Geophysical Models

To estimate the extent and thickness of the rhyolites, geophysical models with a density contrast of +0.36 Mg/m^3 were set up. The upper surfaces of the models were described by polygonal structural contours and the lower surfaces were taken as being horizontal. The gravity effects of the models were determined using the method of Talwani and Ewing (1960). To simplify the calculations the effects were computed at points on a regular, 0.5 km grid at the mean elevation of the gravity stations. Strictly, the gravity effects should be computed at the station positions (both laterally and vertically), however, in view of the assumptions already made in deriving the second order residual anomalies, a smct interpretive method was not used. The maximum error introduced by adopting this simple interpretive method is estimated to be about 10 µN/kg; about 10% of the amplitude of the anomalies.

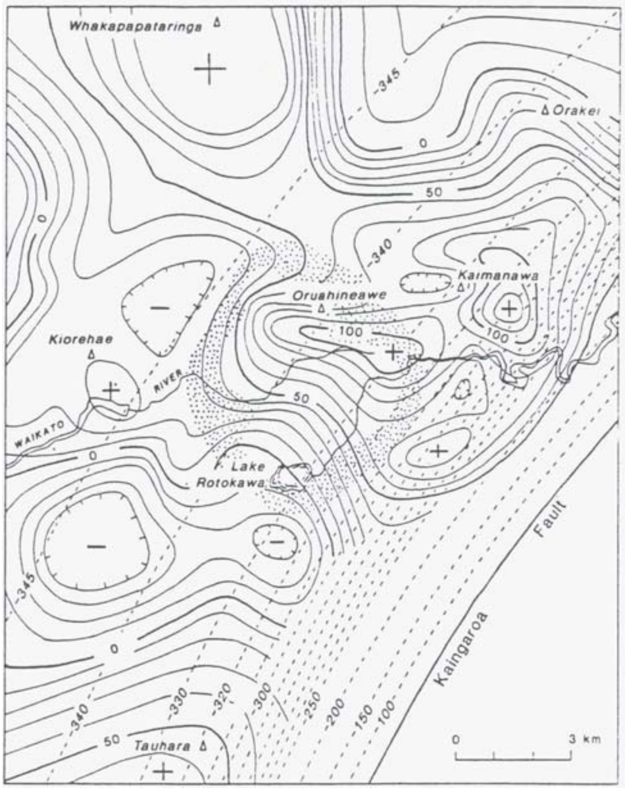

Fig. 5: First and second order residual anomalies (µN/kg) determined using the Rotokawa densityldepth model (Model A, Fig. 3). Solid lines indicate second order anomalies; broken lines the first order anomalies. The dotted area marks the boundary of the Rotokuwa Geothermal Field.

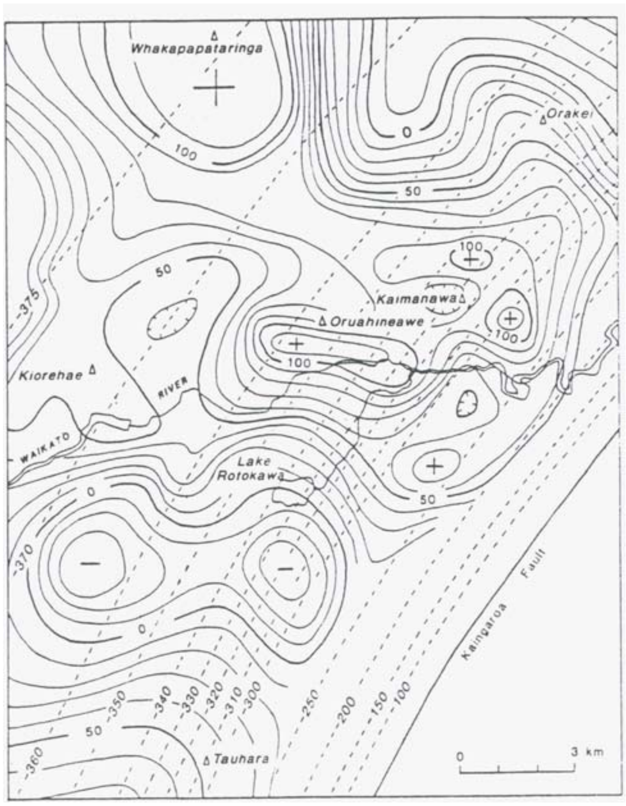

Fig. 6: First and second order residual anomalies (µN/kg) detennined using the Wairakei densityldepth model (Model B, Fig. 3). Solid lines indicate second order anomalies; broken lines the first order anomalies.

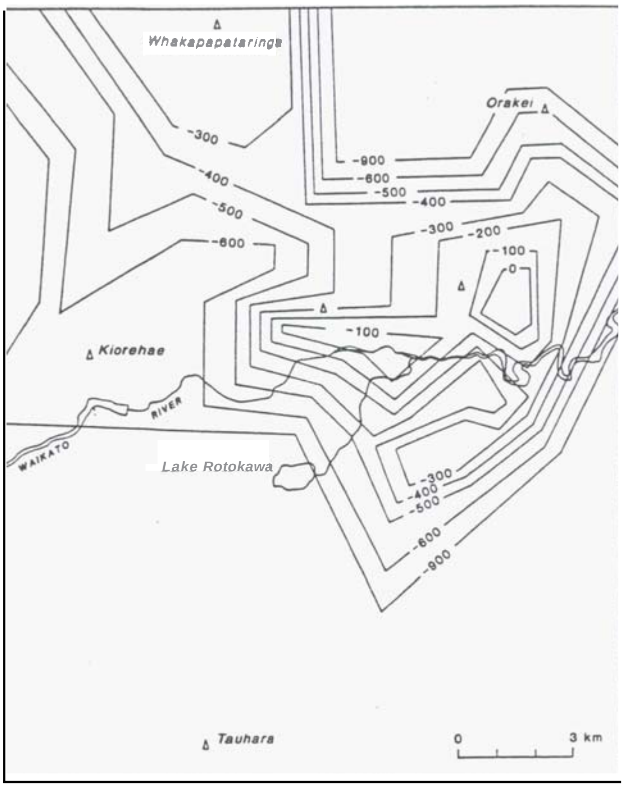

Fig. 7: Geophysical model for the rhyolites. Solid lines indicate contours of depth (m below ground level) of the upper surface of the rhyolite bodies; the lower surface is at -900m. The density contrast used in the model is +0.36 Mg/m³ (360 kg/m³).

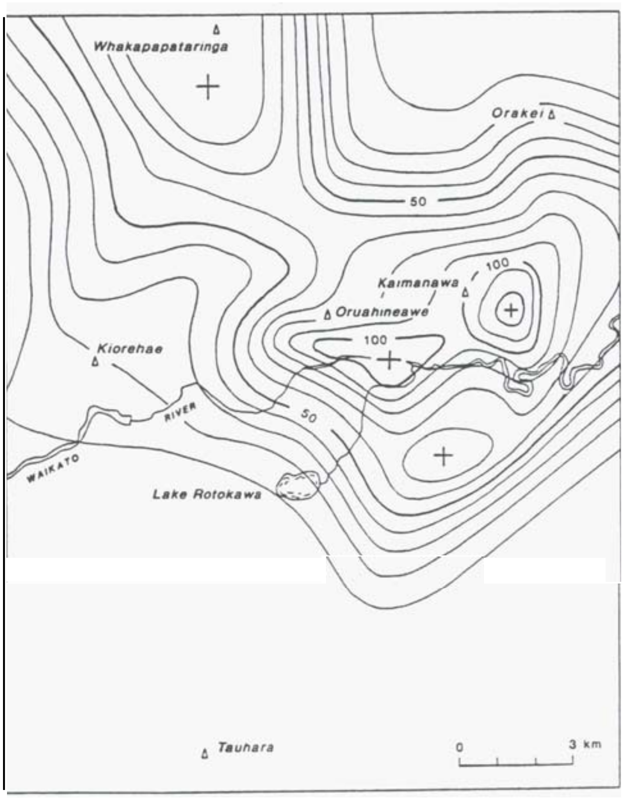

Fig. 8: Gravity effects (μN/kg) of the geophysical model shown in Fig. 7. Contour interval 10 μN/kg.

A geophysical model whose gravity effects are similar to the second order residual anomalies is shown in Fig.7, and its gravity effects are shown in Fig.8. It should be clearly understood, however, that there is no unique model whose gravity effects match the second order residual anomalies. Indeed, the model conflicts in places with other data. The model does not account for the known surface outcrops on Oruahineawe and Kaimanawa; and it predicts the thickness of rhyolite in the vicinity of RK6 to be about 800 m, whereas only about half that amount was encountered in the drillhole. Such conflicts are probably due mainly to local density variations which have not been accounted for in the reduction of the data or in the model, and to the assumption that the rhyolites form a single body rather than a series of adjacent bodies. Nevertheless, the gravity data provides some general information about the distribution of the rhyolites. The model suggests that rhyolites extend, at depth, over a wide area in and around the Rotokawa Geothermal Field. The rhyolites almost certainly extend, at depth, between Oruahineawe and Whakapapataringa, but the gravity data is not able to resolve whether they form a single continuous flow or a number of separate, possibly overlapping, bodies.

The model (Fig.7) predicts the following thicknesses of rhyolite in the drillholes (actual thicknesses encountered are given in brackets):

RK1	350 m (420)	RK2	300 m (400)
RK3	150 m (370)	RK4	400 m (460)
RK5	450 m (470)	RK6	800 m (410)

The thicknesses predicted in the vicinity of RK1, RK4, and RK5 are similar to those encountered; but those predicted in RK2 and RK3 are much less, and that for RK6 is much greater than encountered

RK2 and RK3 are the southernmost drillholes, and lie closest to the negative residual anomaly that lies to the south and south-west of the field. The effect of this negative anomaly, which was not accounted for in the models because little density data is available in that area, is to reduce the gravity effect and hence also the predicted thickness of the rhyolites. Data from drillhole WK227, located in the north-westem part of this negative anomaly, suggest that rocks in this area are about 0.3 Mg/m³ less dense than those at corresponding depths in the Rotokawa Field (Fig. 9). Calculations show that the maximum gravity effect of a cylinder of radius 1 km, extending from the surface to a depth of 1 km, and having a density contrast of -0.3 Mg/m³, is about -75 μN/kg. If the rocks encountered in WK227 also occur south and south-west of the field, then the negative anomaly in this area can be explained.

Drillhole RK6 is the northern-most drillhole in the field and lies closest to the known outcrops of rhyolites. Why the model predicts the rhyolite here be about twice as thick as is found is puzzling. One explanation is that the first order residual anomalies are incorrect; but if this were so then it would be expected that the rhyolite thicknesses in nearby holes would be grossly overestimated, and this is not so. Another explanation is that the densities of the rhyolites vary laterally, with those in the vicinity of RK6 being more dense than those elsewhere, but the data presently available does not support this. A further explanation is that the rhyolites do not form a single continuous body as assumed in the models, but occur as a number of discrete, but closely separated, dome shaped bodies, and that the drillhole has penetrated the thin edge of one such body; this is "special pleading" and does not provide a wholly satisfactory answer.

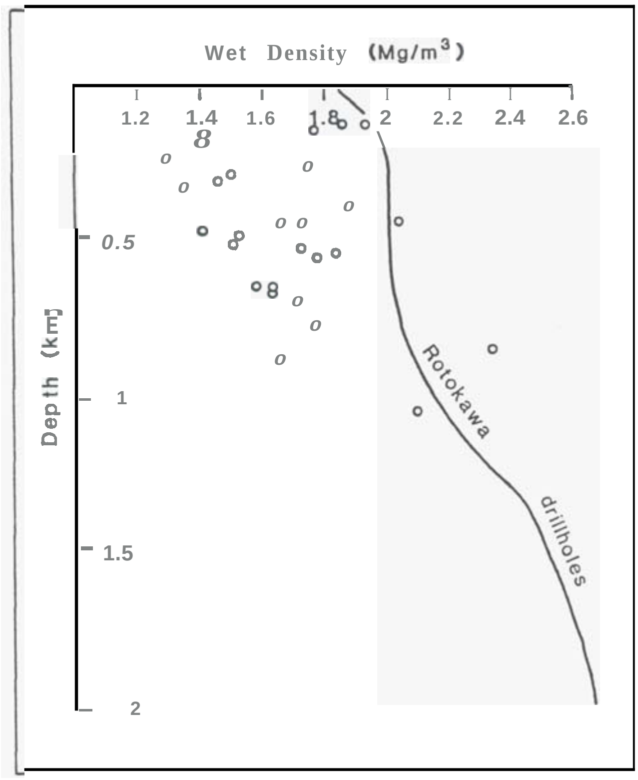

Fig. 9: Plot of wet density against depth for rocks from drillhole WK227. The solid black line shows the density/depth relationship adopted in interpretation of the first order residual anomalies. Note that most of the rocks in WK227 are much less dense than those at Rotokawa.

Until further drilling, in other parts of the field, has been completed and the information made available, it will not be possible to make a more detailed interpretation of the gravity data.

A general conclusion that can be drawn from the modelling is that relatively large (>100 μN/kg) positive residual gravity anomalies, extending over tens or hundreds of square kilometres in area, can occur in the CVR as the result of dense lava flows and domes at shallow depth (<1 km). Also, density measurements in some drillholes (e.g. WK227) near negative residual anomalies suggest that these anomalies are due to unusually low rock densities (<1.5 Mg/m^3) at shallow depths. This means that measurements of the densities of rocks at shallow depths are vital in order to fully and accurately interpret gravity measurements in the CVR. Simple models which assume a uniform density value for the volcanic cover rocks are clearly inappropriate, and some previous studies (e.g. Modriniak and Studt, 1959; Rogan, 1982) which make this assumption and interpret gravity anomalies in the CVR in terms of variations in basement depth may be wrong.

ACKNOWLEDGEMENTS

We thank Gas and Geothermal Trading (Ministry of Energy) for permission to publish. D. Graham assisted with fieldwork and T.C. Mumme made many of the density measurements. The German Academic Exchange Service (D.A.A.D.) provided some support for C. Harms. We thank W.J.P. Macdonald, G.F. Risk. and S. Sherburn for valuable criticism of the manuscript.

REFERENCES

Beck, A.C.; Robertson, E.I. 1955: Chapter II: Geology and Geophysics in (Grange, L.I. Comp.) Geothermal steam for power in New Zealand. D.S.I.R. Bulletin 117.

Grindley, G.W. 1961: "Geological Map of New Zealand 1 : 63,360", Sheet N94 - Taupo. DSIR, Wellington, New Zealand.

Hochstein, M.P.; Henrys, S.A. 1989: Geophysical structure and densification of producing layers in the Broadlands-Ohaaki field. Proceedings of the 11th N.Z. Geothermal Workshop: 45-49.

Hochstein, M.P.; Hunt, T.M. 1970 Seismic, gravity, and magnetic studies, Broadlands Geothermal Field, New Zcaland. Geothermics Special Issue 2: 333-346.

Modriniak, N.; Studt, F.E. 1959: Geological structure and volcanism of the Taupo-Tarawera district. N.Z. Journal of Geology and Geophysics 2: 654-864.

Robertson, E.I. 1951: Gravity survey of the Wairakei-Taupo area in "Results of D.S.I.R. Geothermal Investigations, Wairakei-Taupo Area, 1951", unpublished report, D.S.I.R., Wellington, New Zealand.

Rogan, M. 1982: A geophysical study of the Taupo Volcanic Zone, New Zcaland. Journal of Geophysical Research 87: 4073-4088.

Stern, T.A. 1979: Regional and residual gravity fields, Central North Island, New Zealand. N.Z. Journal of Geology and Geophysics 22: 479-485.

________ 1982: Seismic and gravity investigations of the Central Volcanic Region, North Island, New Zealand. Unpublished PhD Thesis, Victoria University of Wellington, New Zealand.

Talwani, M.; Landisman, M. 1959: Rapid gravity computations for two-dimensional bodies with application to the Mendocino Submarine Fracture Zone. Journal of Geophysical Research 64: 49-59.

Talwani, M.; Ewing, M. 1960: Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape. Geophysics 25: 203-225.

Woodward, D.J. 1982: Reduction of gravity observations on the VAX 11/780 Computer. Technical Note 83, Geophysics Division, D.S.I.R., Wellington, New Zealand.