MAGNETIC ANOMALIES OF THE ROTOKAWA GEOTHERMAL FIELD, TAUPO VOLCANIC ZONE, NEW ZEALAND

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SUMMARY - The reduction of aeromagnetic data over the Rotokawa geothermal field discussed in this paper is an example of the complexity of reduction process of magnetic anomalies in volcanic region. Second order residual magnetic anomalies over the Rotokawa area which have been reduced for the normal geomagnetic field, a first order regional field (interpolated from undisturbed magnetic anomalies over outcrops of non-magnetic basement) and magnetic effects of deep (2.5-7 km depths) magnetic crustal masses, still contain the effect of large wavelength anomaly with an amplitude of about +160 nT and a wavelength of about 15 km. Only third *order* residuals outline the local magnetic anomalies associated with demagnetisation of volcanic rocks within the Rotokawa reservoir. Interpretation of these third order residual anomalies by three-dimensional magnetic modelling shows that rocks lying within the low resistivity area are either partially or completely demagnetised, at least down to sea level. Details of the resistivity boundary in the northernmost comer of the field can be interpreted by shallow, demagnetised and conductive rocks which extend beyond the resistivity boundary.

1. INTRODUCTION

The Rotokawa geothermal prospect lies about 10 km east of the Wairakei Geothermal Field. Its structure is well known from various geophysical surveys and a few deep exploration wells. The approximate lateral extent of thermally altered rocks has been mapped by regional DC resistivity surveys (Geophysics Div. DSIR, 1985); multiple bipole-quadrupole surveys have defined the location of a resistivity boundary (G.F Risk, pers.comm., 1985) which has been shown in many publications (Henley and Middendorf, 1985, for example), although Risk's original data have not been published yet. The inferred resistivity boundary encloses an area of about 15 km^2 (Fig. 1). Other published geophysical surveys include a gravity survey (Hunt and Harms, 1990) and a natural potential survey (Hochstein et al., 1990).

The geological structure of the prospect has been assessed from seven exploration wells (RK1 to RK6, and RK8) although the results of the last two wells (RK6 and RK8) are still confidential. Geological sections by Collar (1985), Krupp et al. (1986) and Krupp and Seward (1987) show that the deepest wells penetrated a NW-dipping sequence of Quaternary volcanic rocks about 2.5 km thick which are underlain by greywacke basement. These wells also established that the Rotokawa prospect is a hot water prospect where temperatures of up to 320°C *can* be found at about 2.5 km depth.

2. MAGNETIC SURVEYS OF THE ROTOKAWA FIELD

A low level airborne magnetic survey of the greater Wairakei area was undertaken in 1951/52 by Gerard and Lawrie (1955), which also covered the Rotokawa prospect. No interpretation of these anomalies over the Rotokawa area was attempted; the original data of the survey are no longer available.

In 1984, another low-level airborne magnetic survey of the greater Maroa-Taupo area was undertaken by staff of the Geothermal Institute. This survey also covered the Rotokawa prospect, where the magnetic total force was observed at 760 m elevation (about 300 m above mean terrain) along a set of E-W aligned flightlines *spaced* about 1 km apart (Fig. 1). Magnetic anomalies of the 1984 survey were constructed by van Dijck (1988) using the normal regional magnetic field described by Reilly *et* al. (1978). However, subsequent studies by Soengkono (1990) showed that the residual magnetic anomalies did not attain zero values over outcropping non-magnetic basement and that surveys conducted in different years produced different values of residual anomaly over same areas.

The problem could be traced to poorly defined terms in the regional field of Reilly et al. (1978). which describe secular variation effects. It could be overcome by using the global International Geomagnetic Reference Field (IGRF) of Malin and Barraclough (1981) and by subtracting the effect of 1st and 2nd order long wavelength regional components associated with the Taupo Volcanic Zone (Soengkono, 1990) which produce reduced data with zero anomalies over non-magnetic basement. The 2nd order long wavelength regional anomalies are associated with *deep* magnetic intrusions beneath the Taupo Volcanic Zone (TVZ) which cause large disturbing effects at its edges.

To check for the origin of a significant negative magnetic anomaly on the northern side of the Rotokawa Field over the young rhyolite dome of Oruahinaewe, we conducted a ground magnetic survey in August 1990/91 with the Geothermal Diploma Class, covering a small area in the NW part of the geothermal field.

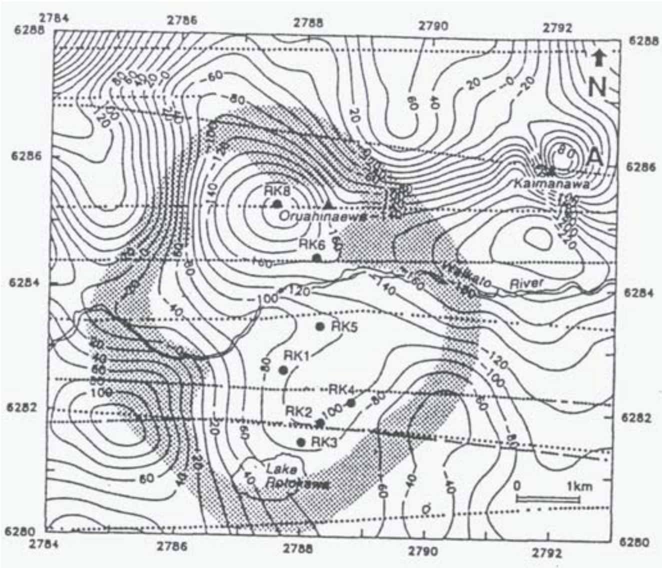

Fig. 1: First order residual total force magnetic anomalies at 760 m a.s.l. over the Rotokawa geothermal field. Contour interval is 20 nT. Flight lines of the survey are shown by dotted lines. The boundary of the geothermal field determined from electrical resistivity measurements is shown by stippled pattern. Solid circles mark the position of drillholes. Grid co-ordinates along the edges of the map are in terms of the NZ Map Grid (km).

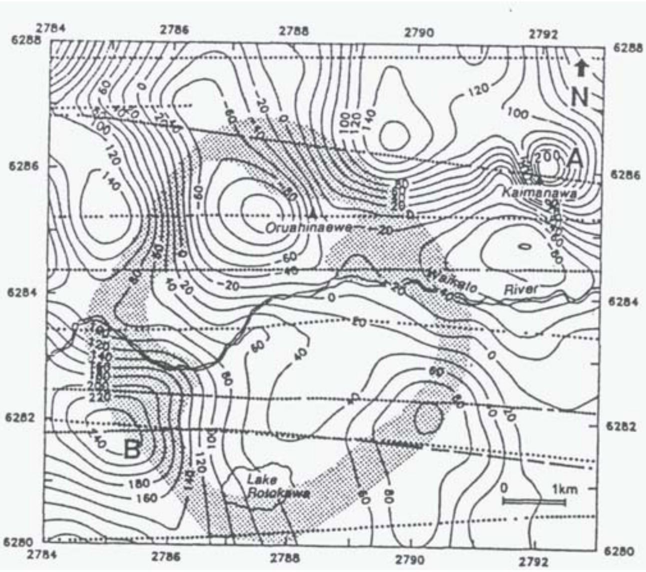

Fig. 3: Second order residual magnetic anomalies at 760 m a.s.l. over the Rotokawa geothermal field. Comments for Fig. I also apply for this figure (locality of drillholes is not shown in this map).

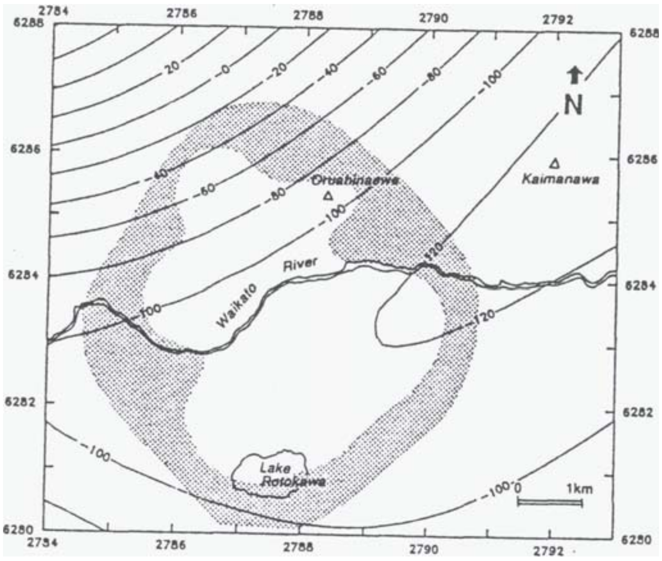

Fig. 2: Magnetic anomaly of deep-seated magnetic masses beneath the TVZ (2 order regional field) at flight level (760 m a.s.l.) over the Rotokawa geothermal field. Contour interval is 20 nT.*

3. RESIDUAL MAGNETIC ANOMALIES (AIRBORNE MAGNETIC SURVEY) OVER THE ROTOKAWA FIELD

Interpretation of magnetic anomalies require the reduction of the normal magnetic field and any disturbing regional effects. In volcanic terrain such reduction can be complex, and the reduction of the airborne magnetic data over the Rotokawa Field is a good example of the complexity of the reduction process in this setting.

If one reduces the airborne data in terms of the 1981 IGRF normal field and subtracts the 1st order regional field defined by interpolation of smooth magnetic anomalies over non-magnetic basement outside the TVZ, one obtains the 1st order residual magnetic anomalies shown in Fig. 1. These anomalies obviously contain effects of another regional field since the positive magnetic anomalies associated with the dipolar magnetic effect of the 535 m high Kaimanawa Rhyolite Dome are depressed (A in Fig. 1). Ground studies have shown that these young rocks lie outside the Rotokawa Field, they are unaltered, and normally magnetised (van Dijck, 1988).

The magnetic effect of deeper crustal magnetic intrusions has recently been analysed by Soengkono (1990) using all available airborne magnetic survey data for the Taupo Volcanic Zone. The magnetic anomaly of the deeper-seated magnetic masses at flight level across the Rotokawa Field are shown in Fig. 2. It can be seen that the horizontal gradient across the prospect is large. If one reduces the effect of the deeper-seated bodies, one obtains the 2nd order magnetic residuals shown in Fig. 3. The positive amplitude of the topographically-controlled bipolar anomaly of the Kaimanawa Dome (A in Fig. 3) has now been restored. Overall, the pattern and magnitude of the residual magnetic anomalies in Fig. 3 is similar to that obtained by van Dijck (1988), who reduced the data by using only the Reilly et al. (1978) normal field. The time variable terms in that field produced an apparent constant shift in the reduced data of about 100 nT, producing an absolute level for the Kaimanawa anomaly which is close to the true zero level given by topographic modelling of this rhyolite dome. At Wairakei, the zero level of residual anomalies obtained with the Reilly et al. field was too low by about 100 nT (van Dijck, 1988). This problem could only be solved by isolating the effects of the deep-seated crustal bodies (Soengkono, 1990). But even the 2nd order residual anomalies shown in Fig. 3 still contain some

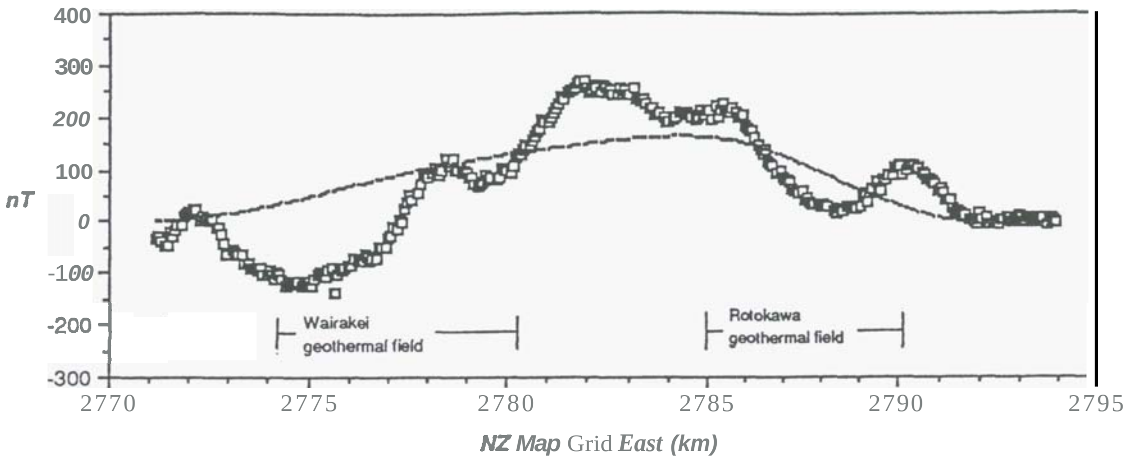

Fig. 4: Second order residual magnetic anomaly profile along the whole length of line 6 across the Rotokawa and Wairakei geothermal fields. An inferred long Wavelength component of the residual anomalies is shown by dashed line.

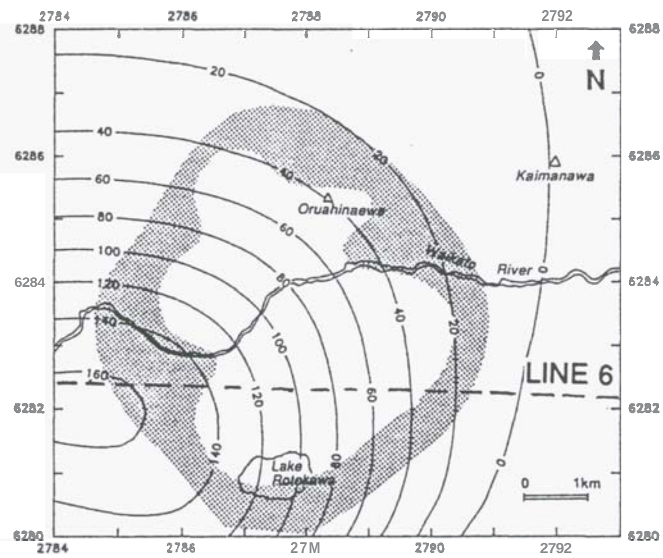

Fig. 5: Inferred long wavelength second order residual anomalies over the Rotokawa geothermal field. Contour interval is 20 nT. The boundary of the geothermal field is shown by stippled pattern.

regional effects. A large positive anomaly (+240 nT at B in Fig. 3) occurs, for example, at the SW edge of the Rotokawa Field. It is not associated with any significant negative anomaly further south (outside the area shown in Fig. 3).

Careful analysis of the regional 2nd order residual anomalies inside and outside the Rotokawa Field showed that these anomalies still contain the effect of a large wavelength anomaly with an amplitude of about +160 nT and a wavelength of about 15 km in W-E direction (see Fig. 4). There are two explanations for this anomaly:

(I) It is part of the deeper-seated effects, and

(II) it is caused by a sheet mass of thick magnetic andesites lying on top of the basement.

Thick, thermally demagnetised andesites were encountered in all deep drillholes at Rotokawa. The long wavelength components of the 2nd order residual magnetic anomalies shown in Figs. 4 and 5 were computed using an inferred NW-dipping body of unaltered andesites lying on top of the basement between the Wairakei and Rotokawa geothermal fields. Similar residual long wavelength effect can also be obtained by a best fit polynomial expression for a set of E-W trending profiles parallel to that shown in Fig. 4.

If one subtracts the effect of the residual long wavelength anomaly in Fig. 5 from the 2nd order residual anomalies (Fig. 3), one obtains 3rd order residual anomalies shown in Fig. 6. The positive anomaly at B is now reduced to +80 nT.

More important, however, is the pattern of the magnetic anomalies inside the Rotokawa Field as defined by resistivity surveys. The anomaly pattern in Fig. 6 shows that a large negative anomaly (up to –160 nT) occurs over the northern part of the field, centred on well RK8. All exposed rhyolitic rocks in the area associated with the Oruahinaewe Dome are thermally altered (steam alteration) and demagnetised. Another smaller negative anomaly (up to –60 nT) occurs over the flat, southern part of the field south of RK1. All negative residual anomalies occur therefore over the thermally altered reservoir as defined by resistivity surveys.

4. RESIDUAL MAGNETIC ANOMALIES OF GROUND SURVEYS

To check the hypothesis that the outcropping rhyolites on the western side of Oruahinaewe Dome are homogeneously demagnetised, we measured the total magnetic farce at ground level in the small (6 km^2) area shown by a framed inset in Fig. 6. The ground magnetic data were reduced in the same way as the airborne data except that the effect of the deep-seated magnetic crustal masses were computed for a mean height of 300 m whereas the 2nd order residual long wavelength effect (to obtain 3rd order residuals) was computed for actual station height.

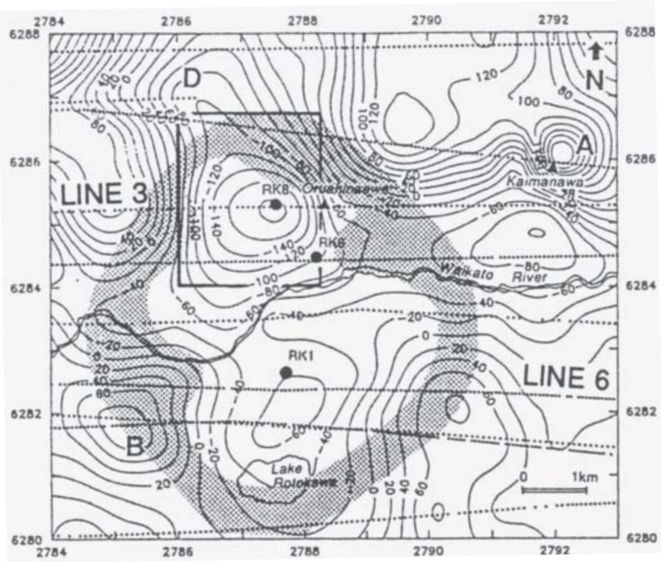

Fig. 6: Third order residual magnetic anomalies at 760 m a.s.l. over the Rotokawa geothermal field. Comments for Fig. I also apply for this figure. Framed inset marks the area covered by Fig. 7.

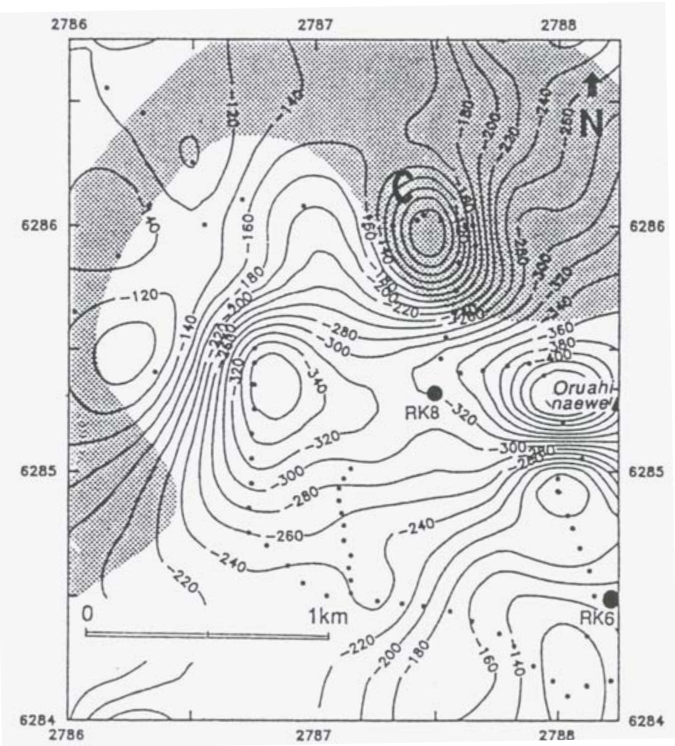

Fig. 7: Third order residual magnetic anomalies at ground level in the NW part of the Rotokawa geothermal field. Small solid circles mark the locality of measurement points. Contour interval is 20 nT. The northwestern boundary of the geothermal field is shown by stippled pattern. Large solid circles are localities of drillholes. Grid co-ordinates along the edges of the map are in terms of the NZ Map Grid (km).

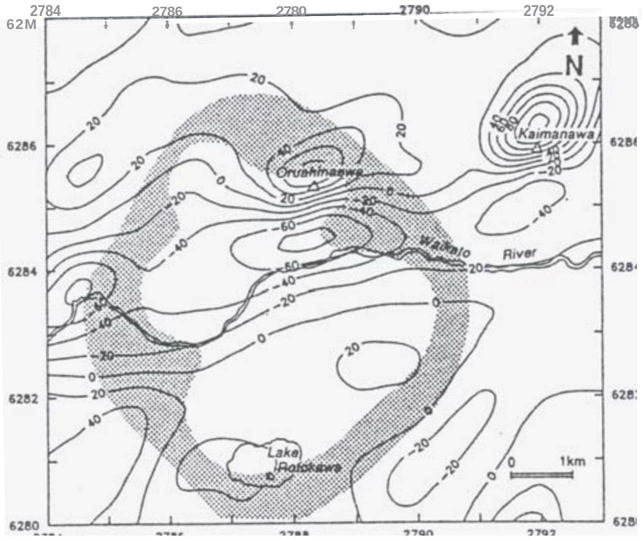

Fig. 8: Magnetic effects of topography (mean total magnetisation = 1.7 Alm) at 760 m a.s.l. over the Rotokawa geothermal field. Contour interval is 20 nT. The boundary of the geothermal field is shown by stippled pattern.

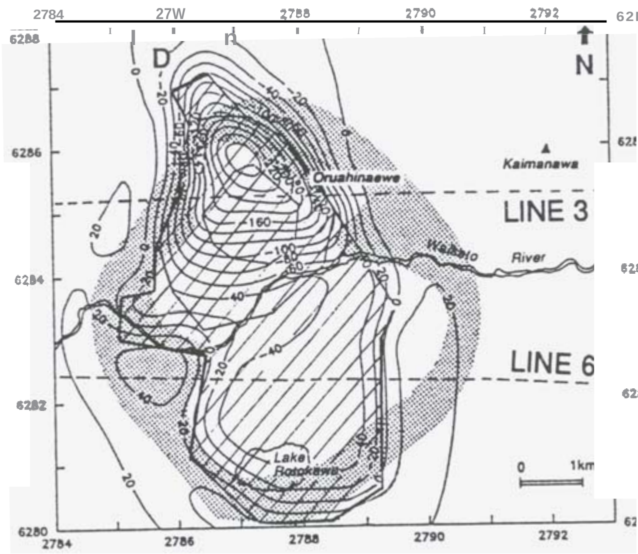

Fig. 9: Magnetic anomaly of a 3-D demagnetisation model of the Rotokawa geothermal field computed at 760 m a.s.l. Contour interval is 20 nT. The lateral extent of demagnetised body at sea level is shown by the hatched area. Stippled pattern marks the boundary of the geothermal field.

The 3rd order residual magnetic anomalies of the ground surveys are shown in Fig. 7. It can be seen that demagnetisation of the Oruahinaewe Rhyolite flows is not homogeneous and that a small portion of the dome lying near anomaly C in Fig. 7 is probably not completely demagnetised. Anomaly C still lies within the broad boundary zone of intermediate resistivities. Ground magnetic surveys can therefore define smaller near-surface alteration structures which cannot be resolved by low level aeromagnetic surveys.

5. INTERPRETATION OF RESIDUAL MAGNETIC ANOMALIES

For interpretation we computed a set of theoretical magnetic anomalies using a **3-D** magnetic modelling algorithm (Barnett, **1976).** All anomaly values were computed for **actual** station (flight) height. Using a trial and error approach and a set of simple models, theoretical anomalies were computed until an acceptable fit with observed data was obtained. The following assumptions were made:

(1) All magnetic **rocks** outside the Rotokawa resistivity boundary are normally magnetised (I = –62°, D = 0°), magnitude of **total** magnetisation = 1.7 A/m; these values **are** representative means for most of the volcanic rocks in the TVZ (Soengkono, *1990).*

(2) Completely demagnetised rocks in the southern Rotokawa Field occur down to sea level; all rhyolites of the Oruahinaewe Dome and deeper rocks **are** completely demagnetised down to **sea** level (level of outcropping rhyolites is between **350** and 500 m).

(3) The lower boundary of the demagnetised rocks is given by plane, horizontal **interfaces.**

(3) Effects of deeper-seated, partly demagnetised **bodies** *can* be neglected, **as** well **as** effects of concealed magnetic bodies outside the field which might attain a magnetisation > 1.7 A/m.

The topographic effect of a simplified terrain model (at flight elevation) is shown in Fig. **8;** for this, the topography was digitised in the form of a grid with a 0.9 km spacing, and further subdivided *to* construct **triangular** facets. The grid size is probably not sufficient to model exactly the topographic effect of **the** Kaimanawa Dome although the computed anomaly **(A** in Fig. 8) **has** the same wavelength **as** the observed one. This anomaly **has** been modelled in detail by van Dijck **(1988)** using a *set* of laminar **bodies** of polygonal **shape;** he found that the best fit magnetisation of this dome lies between 2 and *2.5* **A/m.** The anomalies in Fig. **8** also indicate that the magnetisation of this body **has** *to* be > 1.7 A/m.

If one compares the anomaly pattern in Fig. 6 with that in Fig. **8,** it **can** be *seen* **that** the topographic bipolar effect of the Oruahinaewe Dome does not occur in the observed anomaly. **Our** assumption that this dome is completely demagnetised is therefore justified. The negative bipolar anomaly of **the** dome in Fig. **8** is slightly enhanced by *the* topographic effect of the Waikato River valley.

As a next **step,** we computed the theoretical anomalies **(at** flight elevation) of a set of simple demagnetised **bodies** lying inside the low resistivity structure, vertical extent of demagnetised bodies down to **sea** level. We did not **try** to model every detail of the observed anomalies shown in Fig. 6 but finished modelling after **an** approximate fit between the observed and computed anomalies was obtained. The computed anomalies are shown in Fig. *9;* the lateral extent of the demagnetised body at *sea* level is shown in the same figure. Observed (3^{rd} order residual anomalies) and computed magnetic profiles along lines 3 and 6 *are* shown in Figures 10a and **10b** together with sections of three-dimensional model of demagnetised **rock** inside **the** Rotokawa reservoir.

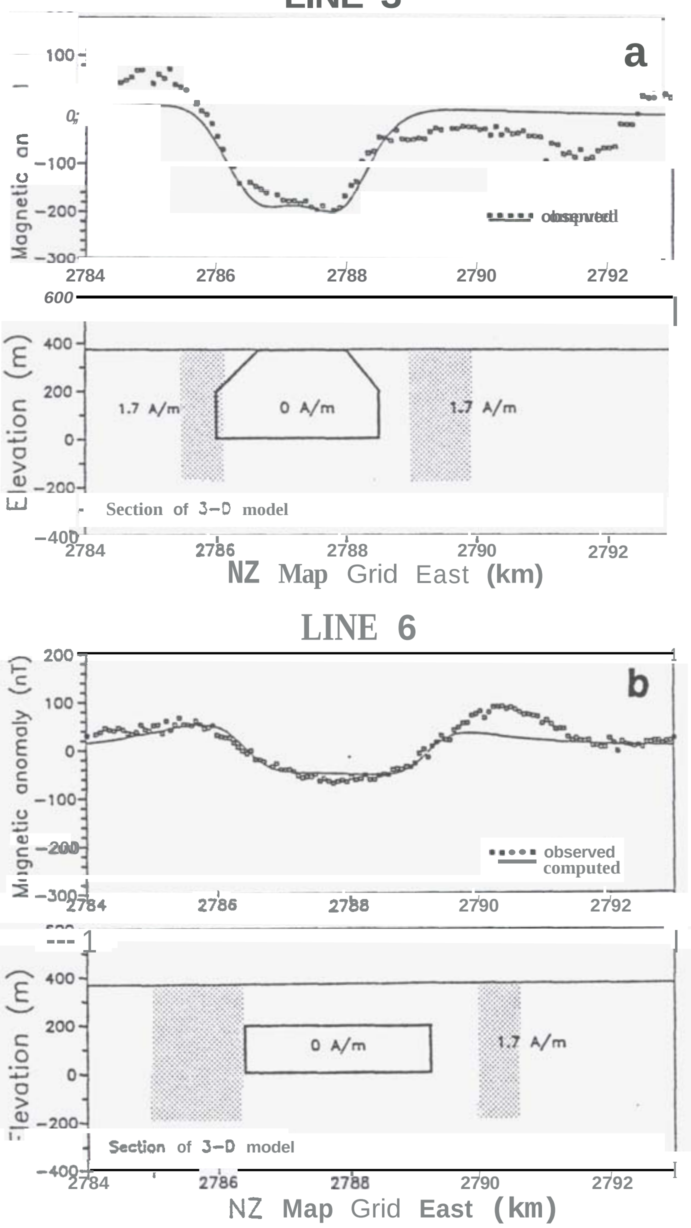

Fig. 10: Observed, computed residual magnetic anomalies (760 m a.s.l) and cross section of the 3-D demagnetised model along flight lines 3 (figure 10a) and 6 (figure 10 b) over the Rotokawa geothermal field. The vertical boundary of the geothermal field is shown by stippled pattern.

A comparison of the contour pattern in Fig. **9** with that in Fig. 6 shows that, overall, **an** acceptable fit has been achieved. It is of interest to note that the 'edge effect' of the demagnetised body produces a semicircular pattern of slightly positive anomalies in the southern part of the Rotokawa Field. The computed anomalies (+20 to +40 nT) **are** less than those up to +60 nT in Fig. 6, but **the** magnitude of **the** computed negative anomaly in **the S** part of the field is **also** lower **than** the observed one shown in Fig. 6. The computed anomaly in the N part of the Rotokawa Field is greater (–240 nT) **than** the observed one **(–160** nT). **This** indicates that not all rocks in the N part are completely demagnetised down to **sea** level; reducing the level of **the** lower *boundary* would produce better **fits.**

Magnetic modelling also allows a better understanding of the resistivity boundary structure. The contour pattern in

Fig. 6, for example, indicates that demagnetised rocks occur probably at shallow depth outside the low resistivity boundary in the northernmost part of the field (anomaly D). To model the magnetic pattern in this part we extended the demagnetised body in this area (and only in this area) beyond the resistivity boundary (see Fig. 9). A close look at the resistivity invariants of the unpublished bipole-quadrupole resistivity survey shows indeed a disturbing effect of a narrow conductive body in the same area. Furthermore, the direction of the invariant ρ_{max} inside the resistivity low indicates a significant N-S trending structure which extends from Lake Rotokawa in the south to the northernmost area shown in D in Fig. 9 (G.F. Risk, pers.comm.). The same structure probably causes the N-S alignment of the magnetic lows shown in Fig. *6.* At point D, the structure extends outside the inferred resistivity boundary.

6. SUMMARY

Analysis of low level aeromagnetic data over the Rotokawa Geothermal Field has shown that residual total force magnetic anomalies based only on the reduction of the normal geomagnetic field are still disturbed by the magnetic effects of deep-seated, crustal magnetic masses (probably located at depths of 3 to 7 km, according to Soengkono, 1990). In the past, the effect of these masses was simply reduced by adding a constant value to the residual anomalies (Rogan, 1982). This procedure produces quite acceptable results for magnetic anomalies in the central part of the Taupo Volcanic Zone.

For prospects lying at the eastern edge of the TVZ, where the disturbing effect of the deeper-seated masses is significant, such procedure does not produce representative residual magnetic anomalies. Unfortunately, the regional magnetic effects of the deeper masses is not well known for the whole TVZ; a recent analysis of this effect by Soengkono (1990) probably describes only fist order effects. This study has shown that higher order regional effects can still be defined from analysis of 2nd order residual anomalies.

Only 3rd order residual anomalies outline the local magnetic anomalies associated with the demagnetisation of the upper part of the Rotokawa reservoir. Having defined the 3rd order residuals, it was found that they contain important information about the reservoir structure.

Interpretation of the 3rd order residual anomalies by 3-D magnetic modelling shows that all rocks lying within the low resistivity area are either partially or completely demagnetised, at least down to sea level. Details of the resistivity boundary in the northemmost corner of the field can be interpreted by shallow, demagnetised and conductive rocks which extend beyond the resistivity boundary.

Magnetic anomalies from ground magnetic surveys also allow a better understanding of a 'fine structure' of shallow, partially demagnetised rocks lying within the zone of intermediate resistivity which defines *the* resistivity boundary.

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