DISTRIBUTION, AGE AND HYDROTHERMAL ALTERATION OF QUATERNARY VOLCANIC ROCKS IN THE TAUPO VOLCANIC ZONE (NORTH ISLAND, NEW ZEALAND) SEEN FROM HIGH RESOLUTION AIRBORNE MAGNETIC DATA

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ABSTRACT

High resolution airborne magnetic data over the central part of TVZ were interpreted in a simple and direct way using some standard magnetic anomaly processing techniques to assess the distribution, general age and hydrothermal alteration of the Quaternary volcanic rocks in this area. The magnetic anomalies were first “reduced to the pole”. This standard magnetic processing moves centres of anomaly to positions above their sources. In region of Quaternary volcanic rocks such as TVZ, high values of reduced to the pole (RTP) anomalies (magnetic highs) often mark the locations of lavas and welded ignimbrites. Two other types of magnetic processing techniques known as the “first vertical derivative” and “analytic signal” were used to help identify anomalies associated with near surface sources.

The GNS Schlumberger apparent resistivity data across TVZ were used to identify magnetic lows (low values of RTP anomalies) that are likely to be associated with hydrothermal alterations of the volcanic rocks, including those by systems that are no longer active. The resistivity data were also used to detect magnetic lows that could be caused by older (>730ka), reversely magnetised volcanic rocks

This direct interpretation indicates that older (>730ka) volcanic rocks are widespread in the TVZ. The results also demonstrate the value of airborne magnetic survey in the exploration and investigation of geothermal systems in a Quaternary volcanic area. Similar interpretation can be applied to other geothermal systems hosted by young volcanic rocks elsewhere. Airborne magnetic data are often already available over geothermal fields worldwide from surveys conducted by government agencies or mineral exploration companies.

1. INTRODUCTION

A detailed airborne magnetic survey was carried out by the NZ gold exploration company Glass Earth Limited in April-July 2005 over a large part of central TVZ (Figure 1) at 60m altitude draped over terrain. Flight lines were flown in an EW direction at 150m spacing with tie-lines in a NS direction at 1500 m spacing. The complete set of the high resolution airborne magnetic data from this survey were kindly provided by Glass Earth Limited to be used for research at the GNS Science.

The following notes discuss a simple and direct interpretation of these high resolution airborne magnetic data in terms of the distribution, age and hydrothermal alteration of Quaternary volcanic rocks in the TVZ.

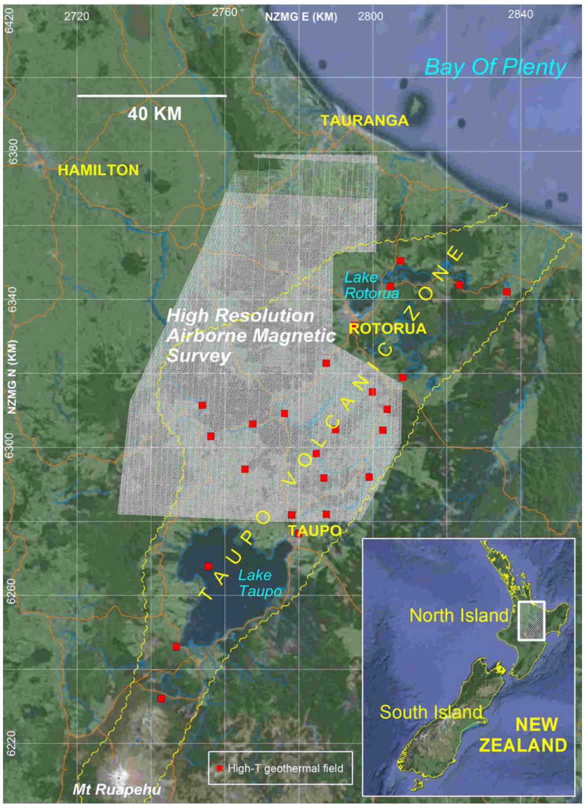

Figure 1: Location map of high resolution airborne magnetic survey over central TVZ.

2. INTERPRETATION METHODS

For this interpretation the (total) magnetic anomalies were reduced to the pole (RTP). This standard magnetic processing technique removes the asymmetries caused by a non-vertical magnetization or regional field (Dobrin and Savit, 1988). The processing moves centres of anomaly to positions above their sources. Shown in Figure 2 are the reduced to the pole (RTP) anomalies over the survey area.

The next step of interpretation is a simple separation between magnetic highs (defined as RTP>200nT) and magnetic lows (defined as RTP<-200nT), see Figure 3. These definitions of magnetic highs and lows are somewhat arbitrary but sufficient for the purpose of this simple and direct interpretation.

Two other types of standard magnetic processing, the vertical derivatives (Dobrin and Savit, 1988) and analytic signal (Nabighian, 1972, Roest *et al*., 1992) were used to help identify anomalies associated with shallow sources. The first vertical derivative (1VD) of the total magnetic field T gives the vertical gradient of the anomalies ($=\partial T/\partial z$). Roest *et al.* (1992) showed that the amplitude (absolute value) of the analytic signal (ASig) at location (x,y) can be obtained from the three orthogonal gradients of T using the expression:

$$|ASig\ (x,y)| = [\ (\partial T/\partial x)^2 + (\partial T/\partial y)^2 + (\partial T/\partial z)^2\ ]^{1/2}.$$

Shallow, non-flat magnetic sources would produce strong magnetic gradients. Such shallow sources would be associated with maximum and minimum extremities of 1VD and with high values of ASig. Hence, both 1VD and ASig are particularly useful for separating magnetic highs associated with surficial magnetised rocks from those caused by other equivalent sources that do not extend to shallow levels. Results of 1VD and ASig processing of the TVZ airborne magnetic data are shown in Figures 4 and 5, respectively. The distributions of strong 1VD (absolute values greater than 1 nT/m) and strong ASig (values greater than 1.5 nT/m), are shown in Figures 6 and 7, respectively. These defining values are also somewhat arbitrary but, again, are sufficient for the purpose of this simple and direct interpretation to indicate zones of shallow magnetic sources.

The GNS Schlumberger apparent resistivity data over TVZ (Figure 8) were used to help identify magnetic lows that are likely to be associated with hydrothermal alterations of the TVZ rocks (low magnetization and low electrical resistivity), including those by systems that are no longer active. The resistivity data were also used to detect magnetic lows that are likely caused by older, reversely magnetised volcanic rocks (negative magnetization and normal electrical resistivity).

All data and image processing in this study were carried out using the *geosoft Oasis Montaj* software.

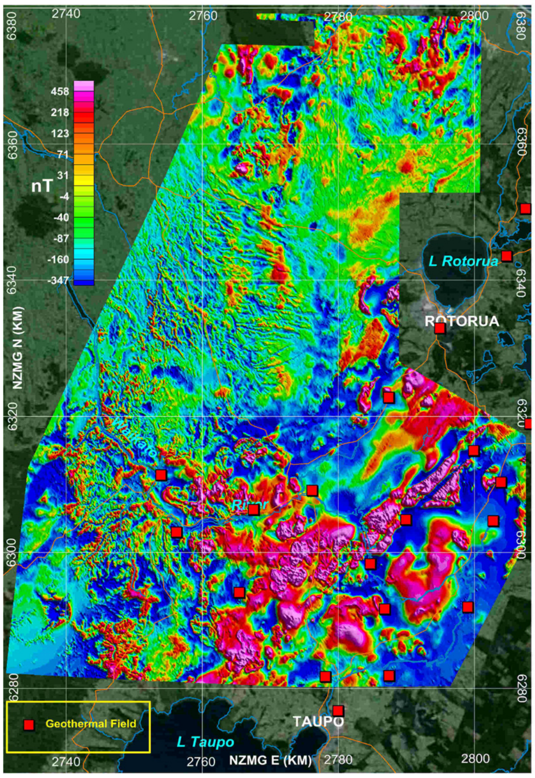

Figure 2: Airborne magnetic anomalies reduced to pole (RTP) over central part of TVZ.

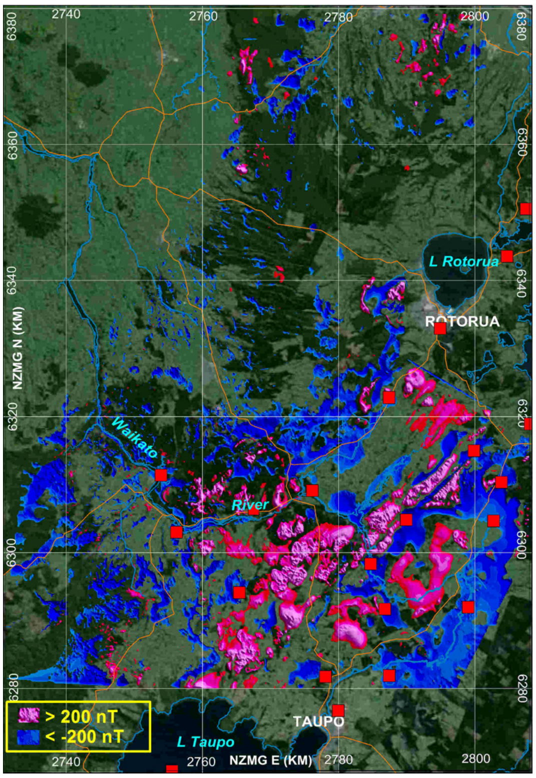

Figure 3: A simple separation between "magnetic highs" (RTP>200 nT) and "magnetic lows" (RTP<-200 nT) over central part of TVZ .

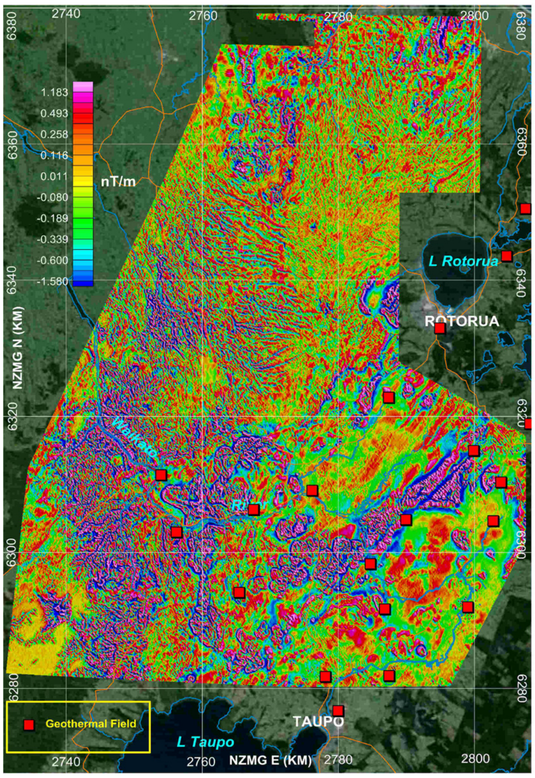

Figure 4: First vertical derivative (1VD) of airborne magnetic anomalies (RTP) over central TVZ.

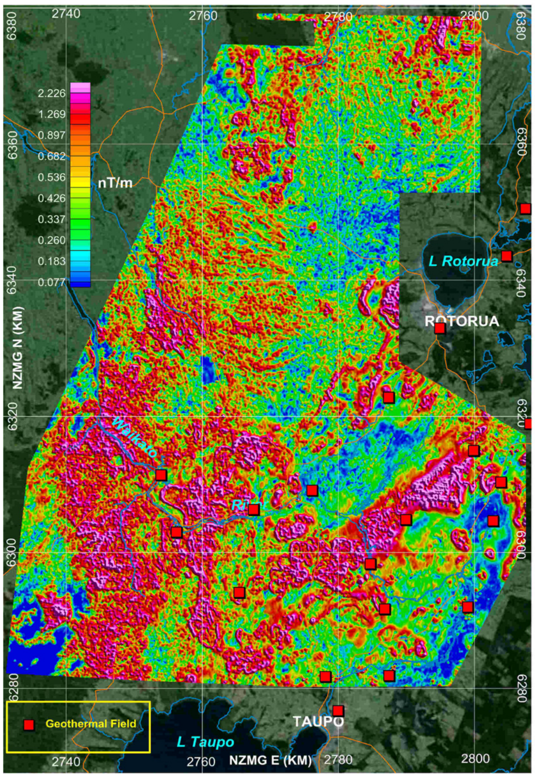

Figure 5: Analytic signal (ASig) of airborne magnetic anomalies (RTP) over central TVZ.

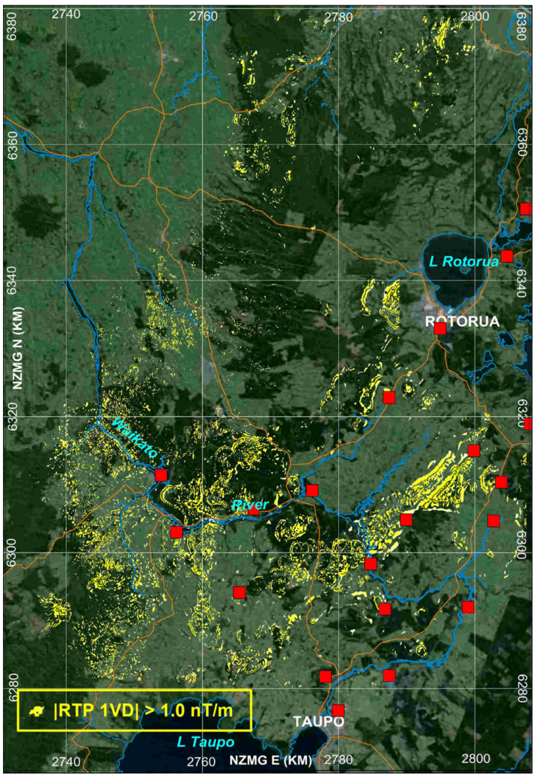

Figure 6: Strong (absolute value >1 nT/m) first vertical derivative (1VD) of airborne magnetic anomalies (RTP) over central TVZ indicating shallow magnetic sources.

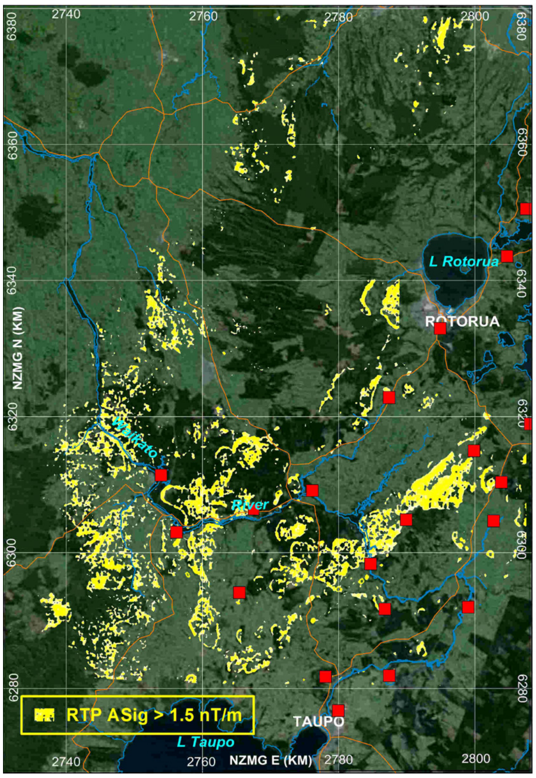

Figure 7: Strong (>1.5 nT/m) analytic signal (ASig) of airborne magnetic anomalies (RTP) over central TVZ indicating shallow magnetic sources.

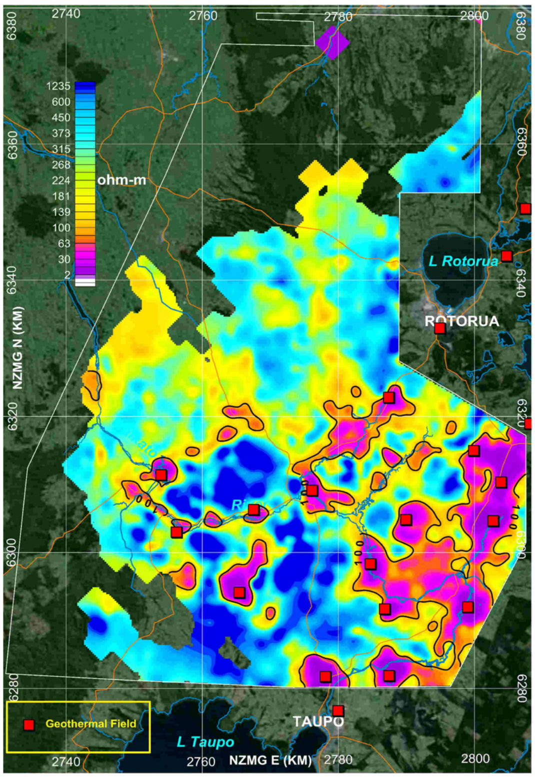

Figure 8: Apparent resistivity distribution from Schlumberger mapping using nominal electrode spacing (AB/2) of 500m. 100 ohm-m contour lines are shown (black lines).

3. YOUNG LAVAS AND WELDED IGNIMBRITES

Lavas and welded ignimbrites usually have relatively high magnetisations. Where these rocks are young and normally magnetised (formed after the last geomagnetic reversal at 730 ka) they would be marked by magnetic highs. Areas where lavas or welded ignimbrites are shallow or exposed at the surface would be associated with magnetic high marked by strong first vertical derivative (1VD) and analytic signal (ASig).

The distribution of the magnetic highs (Figure 3) that are also marked by strong 1VD (Figure 6) and strong ASig (Figure 7) is shown Figure 9. These magnetic highs are the magnetic indicators of surficial lavas and welded ignimbrites. Comparisons between these magnetic indicators and the geological map (Leonard *et al.*, 2010) of the lavas and major welded ignimbrites (also shown in Figure 9) reveal some interesting results:

1. They show strong correlations with majority (but not all) of exposed rhyolite lavas in the Maroa Volcanic Centre (between Mokai, and Orakei-korako geothermal fields), around the Horohoro geothermal field, and west of the Waiotapu geothermal field.
2. They show strong correlations with exposed Whakamaru Group Ignimbrites and Kaingaroa Ignimbrite along the Paeroa Range and Ngakuru Basin (see Figure 9).
3. They show weak or no correlations with some exposed rhyolite lavas in the south-western, southern and south-eastern part of Maroa volcanic centre and most of those of western dome complex (the zone of rhyolite lavas west of Mokai to north-east of Whakamaru and Mangakino).
4. They show almost no correlations with the Whakamaru Group Ignimbrites in the western part of the area shown in Figure 9 and have absolutely no correlation with the Mamaku Ignimbrite to the west of Horohoro. These exposed Whakamaru Group ignimbrites are marked by patches of strong first vertical derivatives and analytic signal. In contrast, the first vertical derivatives and analytic signal are weak over the entire exposures of Mamaku ignimbrite.
5. They also occur over some areas where lavas or welded ignimbrites have not been mapped (such as those between Ngatamariki and Ohaaki).

Detailed 3-D magnetic modelling is being carried out to investigate in particular points 3, 4 and 5 above (part of the author's current research work). It should provide some interesting geological insights into the magnetic characteristics and/or the volcanic stratigraphy of these rocks

Magnetic highs that are not associated with any strong 1VD or ASig mark the presence of buried (sub-surface) lavas or welded ignimbrites that do not extend to shallow levels.

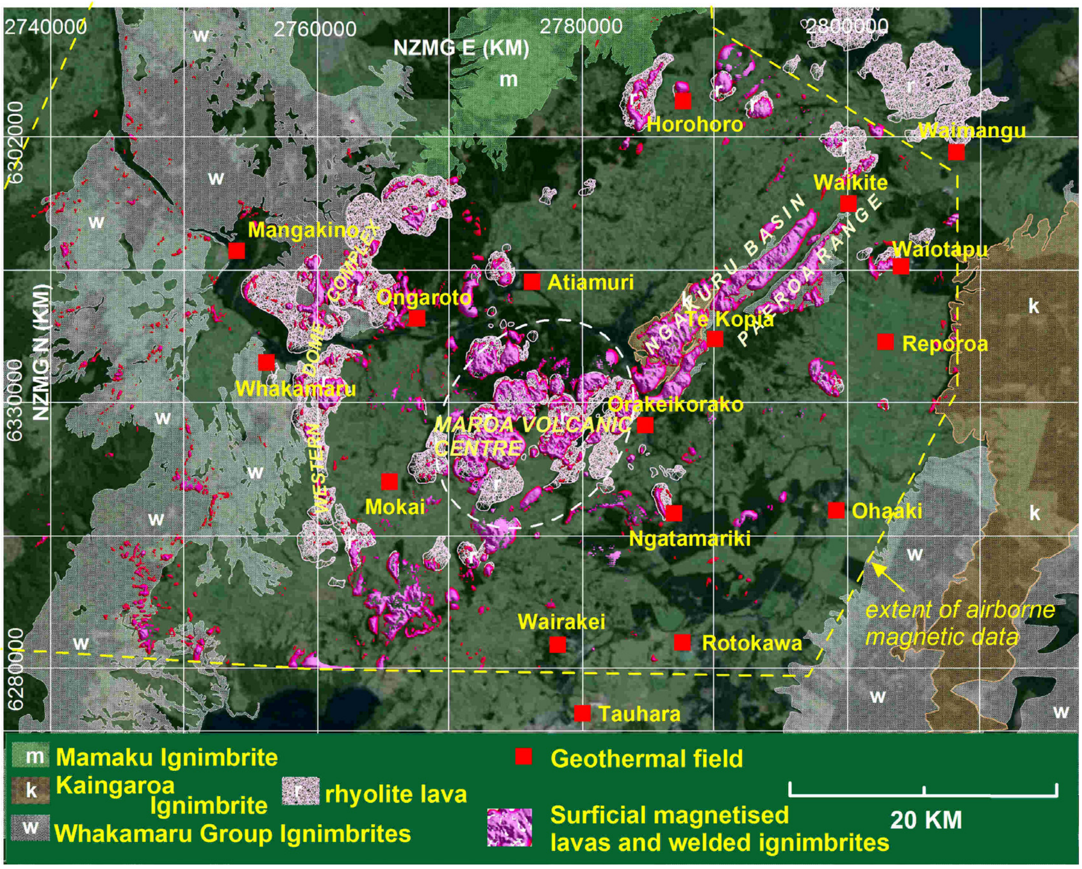

Figure 9: Surficial magnetised lavas and welded ignimbrites over central TVZ as seen by the magnetic data (combination of high RTP and strong 1VD and ASig).

Figure 10 shows the distribution of such sub-surface lavas and welded ignimbrites as seen by the magnetic data. However, it is important to note that subsurface lavas or welded ignimbrites may also exist beneath the surficial magnetic bodies indicated in Figure 9. Detailed 3-D magnetic modeling would be required to resolve this possibility.

The result in Figure 10 provides information on subsurface geology of TVZ. 3-D magnetic modelling studies of such TVZ subsurface magnetic bodies based on lower resolution airborne magnetic data have been carried out over areas to the west of Wairakei (Soengkono and Hochstein, 1992), south-west of Ngatamariki (Soengkono, 1992) and south-west of Reporoa (Soengkono, 2001). The author is currently doing some similar but much more detailed 3-D modelling based on these Glass Earth's high resolution airborne magnetic data. The expected outcomes would provide some better quality interpretation of the subsurface magnetic structures of the TVZ. More importantly, the outcomes would also give us a better understanding on the best way to utilise airborne magnetic data to study any other Quaternary volcanic and geothermal areas. Airborne magnetic survey is the most common and cost effective geophysical survey carried out to investigate a wide variety of geological settings. Data are often already available over volcanic regions and geothermal fields worldwide from surveys conducted by government agencies or mineral exploration companies.

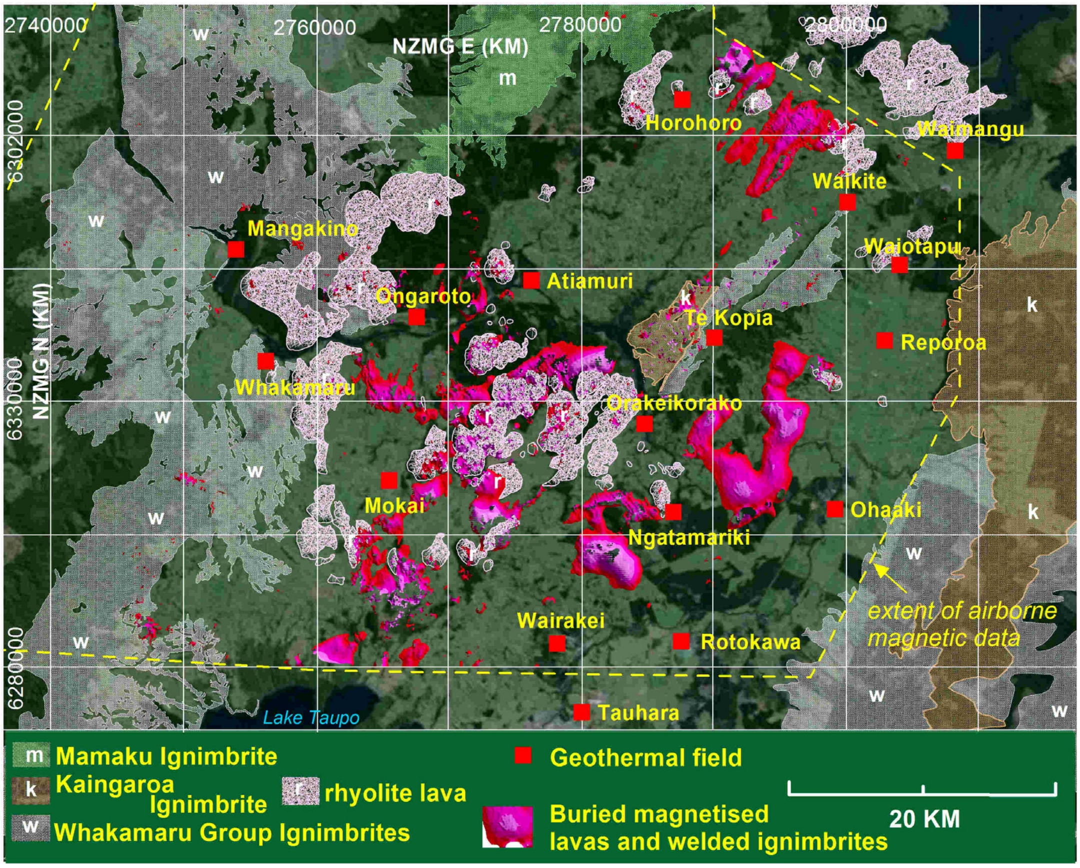

Figure 10: Buried magnetised lavas and welded ignimbrites over central TVZ as seen by the magnetic data (high RTP outside zones of strong 1VD and ASig).

4. HYDROTHERMALLY DEMAGNETISED ROCKS

Hydrothermal activity destroys the magnetisation of volcanic rocks by altering their magnetic minerals (primarily magnetite) into non-magnetic mineral (mainly pyrite). The process is often called hydrothermal demagnetisation. In a Quaternary volcanic area such as TVZ where the geomagnetic field has a high inclination, products of hydrothermal demagnetisation are often marked by magnetic lows that are readily detectable from the result of an airborne magnetic survey. However, magnetic lows can also be produced by reversely magnetised volcanic rocks, i.e. those deposited prior to the last geomagnetic reversal at 730 ka (0.73 million years ago). The two can sometimes be distinguished by comparisons with resistivity data as hydrothermal activities also reduced the electrical resistivity of the volcanic rocks.

Figure 11 shows hydrothermally demagnetised zones in the central TVZ indicated by magnetic lows (see Figure 3) accompanied by low (<100 ohm-m) values of Schlumberger (AB/2=500m) apparent resistivity (see Figure 8). It can be seen in Figure 11 that all TVZ active geothermal fields covered by the airborne magnetic survey are marked by these hydrothermally demagnetised zones. However, there are also hydrothermally demagnetised zones that are not associated with the known geothermal fields. Studies of some such zones by Glass Earth Limited in the search of epithermal mineralisation have provided evidence of fossil geothermal fields. Unfortunately, no economic gold mineralisation deposits were found.

Results of several 3-D magnetic modelling of individual TVZ geothermal systems based on older, low resolution airborne magnetic data have previously been carried out at Mokai (Soengkono, 1985), Rotokawa (Soengkono *et al.*, 1991), Ngatamariki (Soengkono 1992), Wairakei (Soengkono and Hochstein, 1992; Hunt et. al. 2009), Orakeikorako (Soengkono, 1993), Waimangu (Soengkono, 2001) and Reporoa (Soengkono, 2001). Discussions of these studies in terms of the application of magnetic method to assess the extent of high temperature geothermal reservoir in a Quaternary volcanic setting were published by Soengkono and Hochstein (1992) and Hoechstein and Soengkono (1997). The high resolution Glass Earth airborne magnetic data now provide opportunity for further detailed 3D magnetic modelling to determine better magnetic characteristics of TVZ geothermal systems. Such detailed 3D modelling would provide better case study models to help investigating geothermal systems hosted by Quaternary volcanic rocks elsewhere.

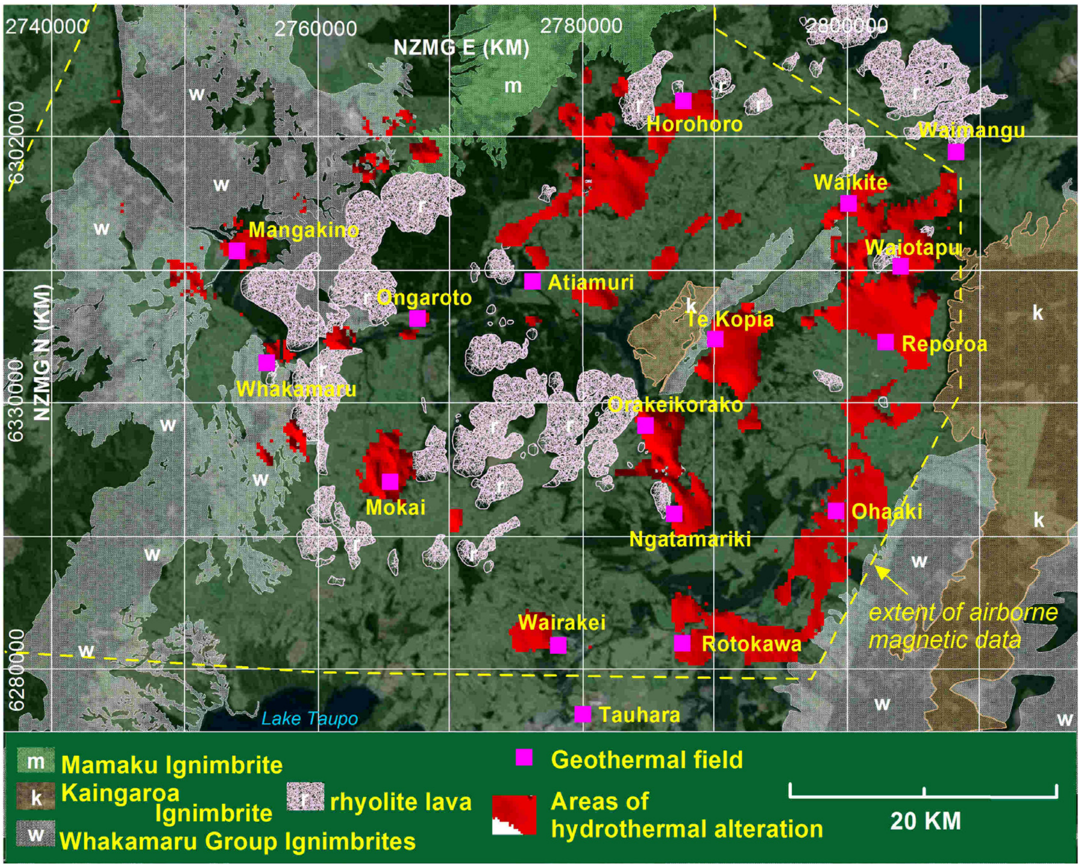

Figure 11: Areas of hydrothermal alteration over central TVZ as seen by the magnetic data (combination of low RTP and Schlumb. app. res. <100 ohm-m).

5. OLDER VOLCANIC ROCKS

Quaternary lavas and ignimbrites that were formed prior to 730 ka (the last geomagnetic reversal) are likely to be reversely magnetised. These can often be recognised from magnetic lows that are not associated with resistivity lows.

Figure 12 shows the distribution of such magnetic lows. The figure indicates areas of old, reversely magnetised rocks in studied area. However, the result shown in Figure 12 is still only preliminary and it needs some further confirmations. For example, the zones that are located close to a strong magnetic high or to prominent topographic lows are needed to be (and will be) checked by detailed 3D modelling to ensure that they are not simply the complementary dipolar components of magnetic high, nor the effects of topographic depression of normally magnetised rocks.

A large number of these possible zones of reversely magnetised rocks appear to occur in the western part of TVZ and over the Mamaku depression west - southwest of Horohoro. This result is consistent with a previous study by Soengkono *et al.* (1992). Some of these western TVZ magnetic lows correlate with exposures of the Ongatiti Ignimbrite, a major western TVZ ignimbrite formation that has been dated (K-Ar dating) at 1.25 Ma (Soengkono, 1990, Soengkono *et al.*, 1992). A magnetic low to the south-southeast of Whakamaru marks a highly eroded small rhyolite dome named Whakaahu (Figure 12). Paleomagnetic samplings and measurements confirmed that both the Ongatiti Ignimbrite and Whakaahu rhyolite are reversely magnetised (Soengkono, 1990; Soengkono *et al.*, 1992).

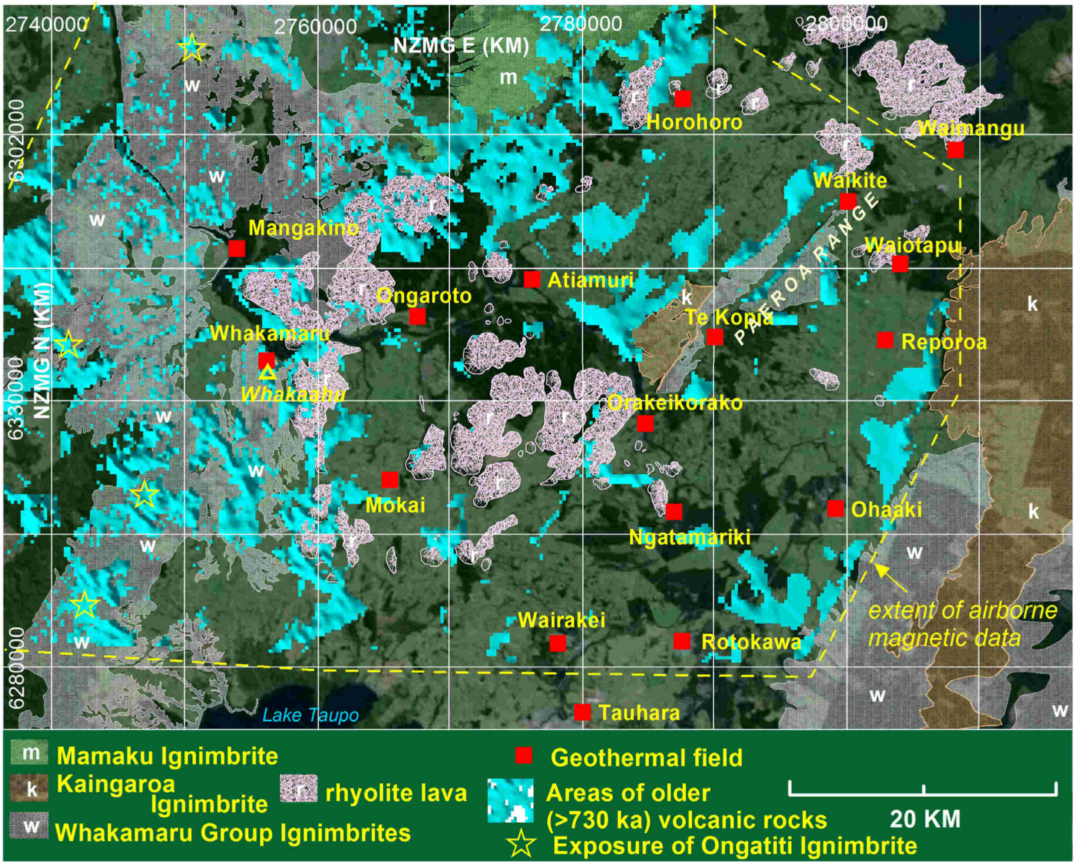

Figure 12: Areas of older (>730 ka) volcanic rocks over central TVZ as seen by the magnetic data (combination of low RTP and Schlumb. app. res >100 ohm-m).

The lack of magnetic highs over the Whakamaru Group Ignimbrites in the western TVZ (Figures 9 and 10) might be associated with these ignimbrites being in a volcanic stratigraphy position above older deposits of the reversely magnetised Ongatiti Ignimbrite. This can (and will) be checked by 3D magnetic modelling.

The results in Figure 12 indicate that older (>730 ka), reversely magnetised rocks are also rather widespread in the eastern TVZ. The existence of reversely magnetized rocks has been reported in the Waiotapu / Paeroa Range area by Grindley *et al.* (1994). U-Pb dating of zircon of altered pyroclastic deposits penetrated by drillholes at Waiotapu, Te Kopia and Orekeikorako geothermal fields also showed that volcanic rocks with ages greater than 730 ka are common in the eastern TVZ (Wilson *et al.*, 2010).

6. CONCLUDING REMARKS

This study has shown that significant geological information can be extracted from high resolution airborne magnetic data using a simple and direct interpretation. Only a minimum bias needs to be introduced to such a direct interpretation.

The TVZ example discussed in this paper shows that such direct interpretation can outline the distribution of surficial and buried lavas and welded ignimbrites. With the help of information on the electrical resistivity of rocks (in this TVZ example such information is provided by results of Schlumberger apparent resistivity mapping) the high resolution magnetic data can also be used to delineate zones of hydrothermally demagnetized rocks, as well as areas where older (>730 ka) reversely magnetic rocks are close to the surface. The extent and distribution of reversely magnetised rocks are important for the understanding of volcanic history and stratigraphy of the studied area.

Results of such simple and direct interpretation also provide good starting points for a further detailed 3-D magnetic modeling of the complex volcanic region, to assess the extent of geothermal reservoirs hosted by the young, mostly magnetised volcanic rocks.

The results of this study also demonstrate the high value of airborne magnetic survey in the exploration and investigation of geothermal systems in a Quaternary volcanic area. Similar interpretation can be applied to other geothermal systems hosted by young volcanic rocks elsewhere. Airborne magnetic data are often already available over geothermal fields worldwide from surveys conducted by government agencies or mineral exploration companies.

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