# 3D IMAGING OF HIGH RESOLUTION AIRBORNE MAGNETIC DATA OVER MOKAI GEOTHERMAL FIELD, NEW ZEALAND

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## ABSTRACT

The first magnetic study of the Mokai Geothermal Field was made back in 1985, based on a low resolution airborne magnetic survey carried out in 1983 at elevations of about 760 m asl by the Geothermal Institute (University of Auckland). More recently, the Mokai area was included in a detailed airborne magnetic survey over the central Taupo Volcanic Zone made in 2005 by the gold exploration company Glass Earth NZ Ltd. The 2005 survey was conducted at 60 m ground clearance along E-W main flight lines separated by 150 m spacing.

A technique for 3D imaging of high resolution airborne magnetic data was developed by the author using a combination of upward and downward continuations and verified by applying it to theoretical *synthetic anomalies* computed for a 3D source model. The aim of the technique is to image, from *actual observed anomalies*, the distribution of magnetisation at different depths.

In the previous 1985 study, the Mokai reservoir was shown to be associated with a simple 3D body of homogeneous zero magnetisation with flat top and base and vertical edges, located between 400 m and 900 m depths (between about +0 m RL and -500 m RL). Inside the body all ferromagnetic minerals (magnetite and titanomagnetite) are inferred to have been completely altered by hydrothermal fluids to non-magnetic sulphide minerals (mainly pyrite). The 3D imaging of the 2005 high resolution airborne magnetic data from this study verified the broad figure of the 1985 3D model. However, the 3D imaging of the 2005 data also reveals details of the hydrothermal demagnetisation associated with Mokai geothermal activity not shown in the 1985 forward modeling result. Two areas of steam heated thermal manifestations appear to be associated with near surface extensions of the hydrothermally demagnetised rocks.

Some zones of low magnetisation detected by the 3D imaging of the 2005 high resolution airborne magnetic survey could be associated with NNE outflow of geothermal fluids from the Mokai field revealed by the result of previous DC-resistivity survey.

## 1. INTRODUCTION

The Mokai geothermal field is located about 25 km northwest of the Taupo in central North Island of New Zealand. Geothermal power generation at Mokai has been developed by the Tuaropaki Power Company (75% Tuaropaki Trust and 25% Mighty River Power) and is currently producing about 110 MW electricity. No confidential data related to the power generation at Mokai are discussed or mentioned in this paper.

Although the occurrence of surface thermal manifestations in the Mokai area had been reported as early as 1937 (Grange, 1937), interest in the geothermal prospect was revived only in 1977, following the result of a multipole-quadrupole resistivity survey by the Geophysics Division of DSIR (the predecessor of GNS) (Bibby, 1977; Bibby et al., 1984). Following this survey, more detailed surveys including Schlumberger resistivity mapping (Bibby et al., 1984) were conducted.

The resistivity surveys show that the surface thermal manifestations at Mokai lie inside a low resistivity region, which has a well-defined boundary everywhere except to the northeast. It was interpreted that the low resistivity region is where the geothermal fluid is flowing upwards. The same fluids are then flowing laterally NNE, towards the North Mokai Springs, under the influence of regional ground water movements.

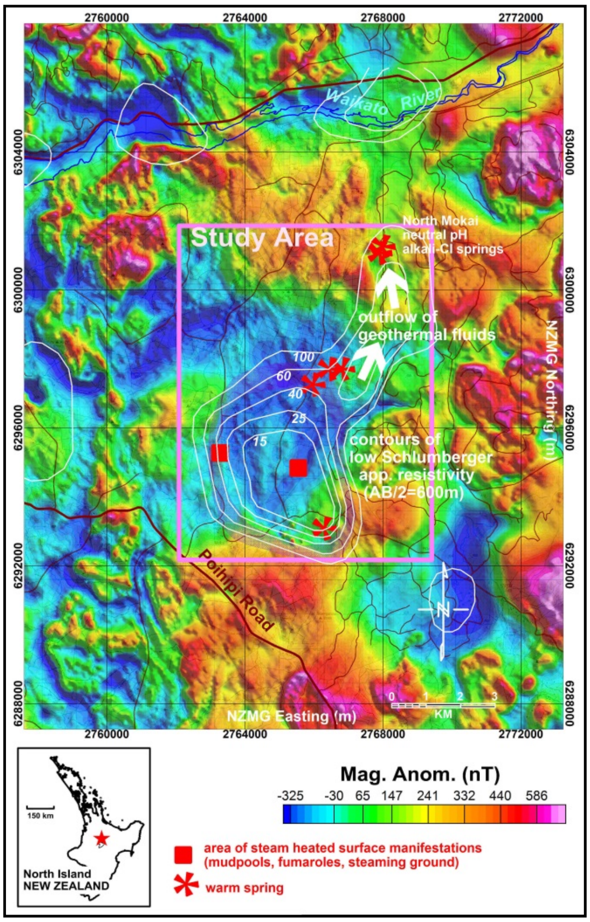


**Figure 1: High resolution magnetic anomalies over the Mokai Geothermal Field.**

A low resolution airborne magnetic survey over the Mokai Geothermal Field was carried out in 1983 by the Geothermal Institute, University of Auckland. The survey was flown at altitude of about 760 m asl along mainly NS flight lines separated by about 1 km spacing (Soengkono, 1985). The result revealed a wide magnetic low associated with the Mokai resistivity boundary. A forward 3D modeling showed that the negative anomalies can be explained by the occurrence of a horizontal polygonal body of hydrothermally demagnetised volcanic rocks inside the Mokai resistivity low, extending down from 400 m to 900 m depths (0 m RL to -500 m RL) (Soengkono, 1985). It was inferred that within the body all ferromagnetic minerals (magnetite and titanomagnetite) have been completely altered by hydrothermal fluids to non-magnetic sulphide minerals, (mainly pyrite).

More recently, the Mokai area was included in an extensive and detailed airborne magnetic survey over the whole central TVZ conducted in 2005 by the gold exploration company Glass Earth NZ Ltd. The 2005 survey was conducted at 60 m ground clearance along E-W main flight lines separated by 150 m spacing High resolution magnetic anomalies obtained from this survey over Mokai area is shown in Figure 1, together with location of surface thermal manifestations and contours of low Schlumberger apparent resistivity of AB/2=600m (indicative of low resistivity values of the ground to about 300 m depth).

The airborne magnetic data in Figure 1 also revealed the wide magnetic low associated with the Mokai geothermal Field. A narrower zone of slightly higher magnetic values can be seen at approximately the centre of this wide magnetic low. This paper presents and discusses a 3D *magnetic imaging* technique and its application to the high resolution magnetic data within the Mokai study area (indicated in Figure 1). All processing and transformations of the magnetic data were made using the *Geosoft Oasis Montaj Software*. The forward computation of 3D magnetic model to check and test the image processing technique was carried out using a computer code written by the author based on the equations published by Barnett (1976)

## 2. A TECHNIQUE FOR 3D IMAGING OF MAGNETIC DATA

The first step for imaging total force magnetic anomalies is reduction to the pole (RTP). This standard magnetic processing technique removes the asymmetries caused by a non-vertical magnetisation or regional field (Dobrin and Savit, 1988). The processing moves centres of anomaly to positions above their sources.

The second step is a *progressive* upward continuation of the RTP anomalies. The upward continuation transformation can be seen as a very-smooth (and stable) low pass filter that attenuates short wavelength anomalies relative to their longer wavelength counterparts (Dobrin and Savit, 1988). As shallow magnetic sources would produce magnetic anomalies with short wavelengths, the upward continuation transformation can also be seen as a removal of magnetic effects caused by the sources located above the *depth* given by the *level* of upward continuation. If the upward continuation is progressively carried out at increasing levels, it would remove the effects of magnetic sources from above depths that are also progressively increasing. Extending this idea further: the *difference* between *values of RTP magnetic data upward continued to a specific level 1* and *the values of the same data but upward continued to the next (higher) level 2* would give the effects of magnetic sources in the layer between *depth 1* and *depth 2*, which would also correspond to the *variation* of magnetisation in that layer. Hence, a series of *difference in values of UPC* (or *diff UPC* for short) data can be obtained, reflecting magnetic variations at progressively increasing depths.

The problem is that there is no clear and direct relationship between the *level* of upward continuation and *to what depth* the effects of magnetic sources have been removed by the upward continuation. An application of the technique to synthetic anomalies computed from a variety of 3D sources would provide the relationship between the *upward continuation levels* and the *known depths* (of the 3D sources). For NZ (where magnetic inclination is about -62.5°) this exercise shows that the actual depths are equivalent to about 0.9 times the upward continuation levels. The exercise also shows that a progressive upward continuation using levels increase by a factor of 1.2 is effective to image the magnetic variation at increasing depths. Furthermore, as upward continuation gives magnetic anomalies that would be observed at higher level, the opposite transformation (downward continuation) can be applied to the *diff UPC* data to bring back their values down to their appropriate depths, to provide a more representative image of the magnetisation variation.

An example of the 3D imaging exercise applied to synthetic anomalies computed from a demagnetised model which has a close affinity to the Mokai demagnetised body is presented in Figure 2. It can be seen in this figure that the 3D imaging can reasonably reveal the source of the anomalies. However, the central top of the source model is rather poorly represented in the 3D imaging result (see the label “artifact of imaging” in Figures 2c and 2d). Such misrepresentation would happen to anomaly source that has wide lateral extension in comparison to its thickness. This is related to the fact that the magnetic effects of infinitely wide source are always zero. Artifacts of imaging also occur around the anomaly source. A detailed forward modeling can refine the result of the 3D imaging and would reduce or eliminate such artifacts.

## 3. THE IMAGING OF HIGH RESOLUTION AIRBORNE MAGNETIC DATA OVER MOKAI GEOTHERMAL FIELD

The 3D imaging technique was applied to the real data from the 2005 high resolution airborne survey inside the Mokai study area marked in Figure 1.

Shown in Figure 3 are two examples of the 3D imaging views as seen from two different angles. Figure 4 shows the map of *diff UPC* from the 3D imaging result sliced at 0 m RL, -300 m RL, -600 m RL and -900 m RL. The cross sections taken from the 3D imaging along profile lines SW-NE and NW-SE (the locations of profile lines are shown in Figure 4) are presented in Figure 5.

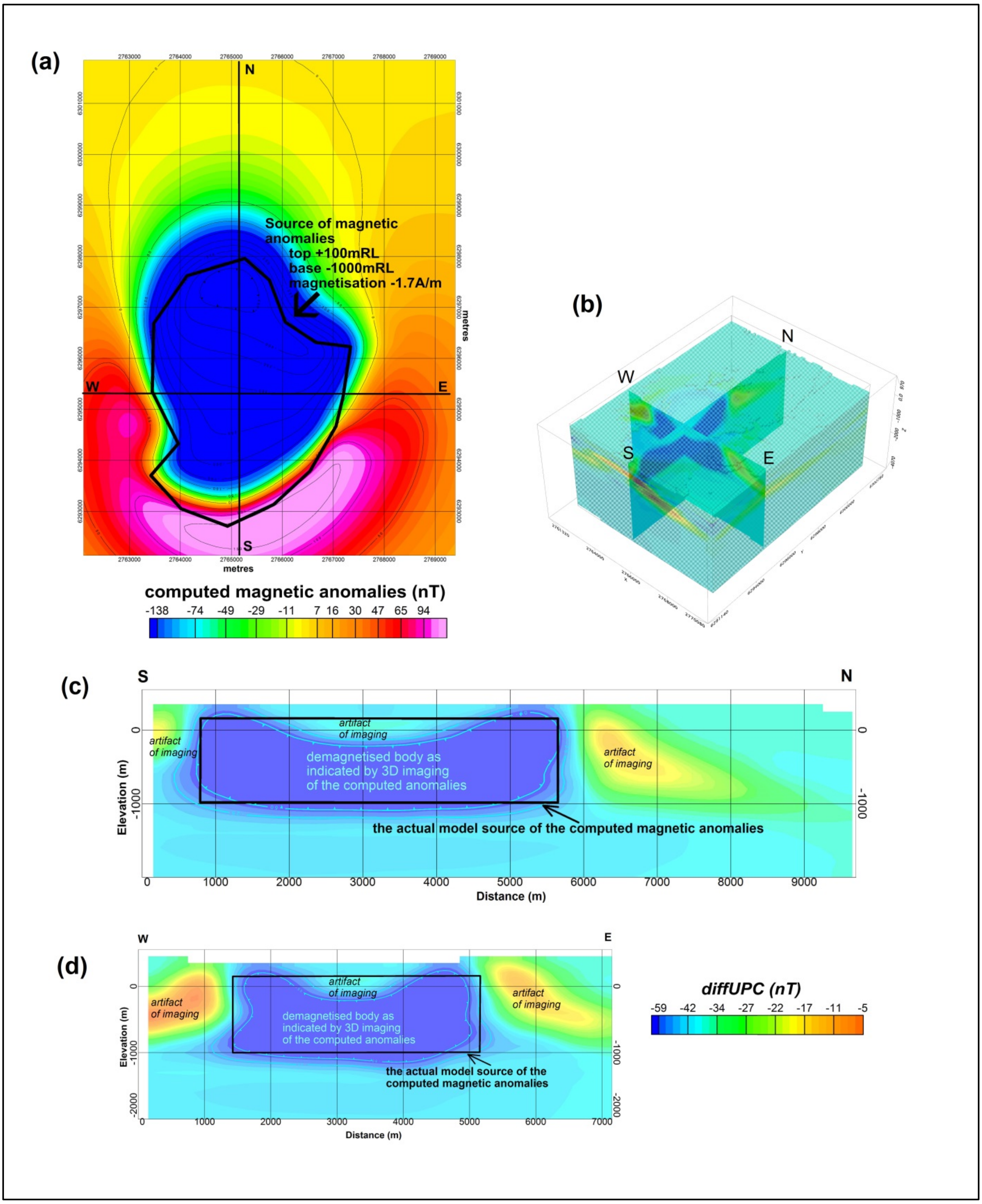


**Figure 2: Example of 3D imaging using reduction to pole (RTP) and progressive upward continuation applied to synthetic anomalies computed for a horizontal polygonal body. (a) Map of the polygonal body and its computed magnetic anomalies; (b) 3D block diagram of *diff UPC* computed for the synthetic magnetic anomalies shown in (a); (c) SN profile showing the cross-section of source body and the colour image of *diff UPC*; (d) WE profile showing the cross- section of source body and the colour image of *diff UPC*.**

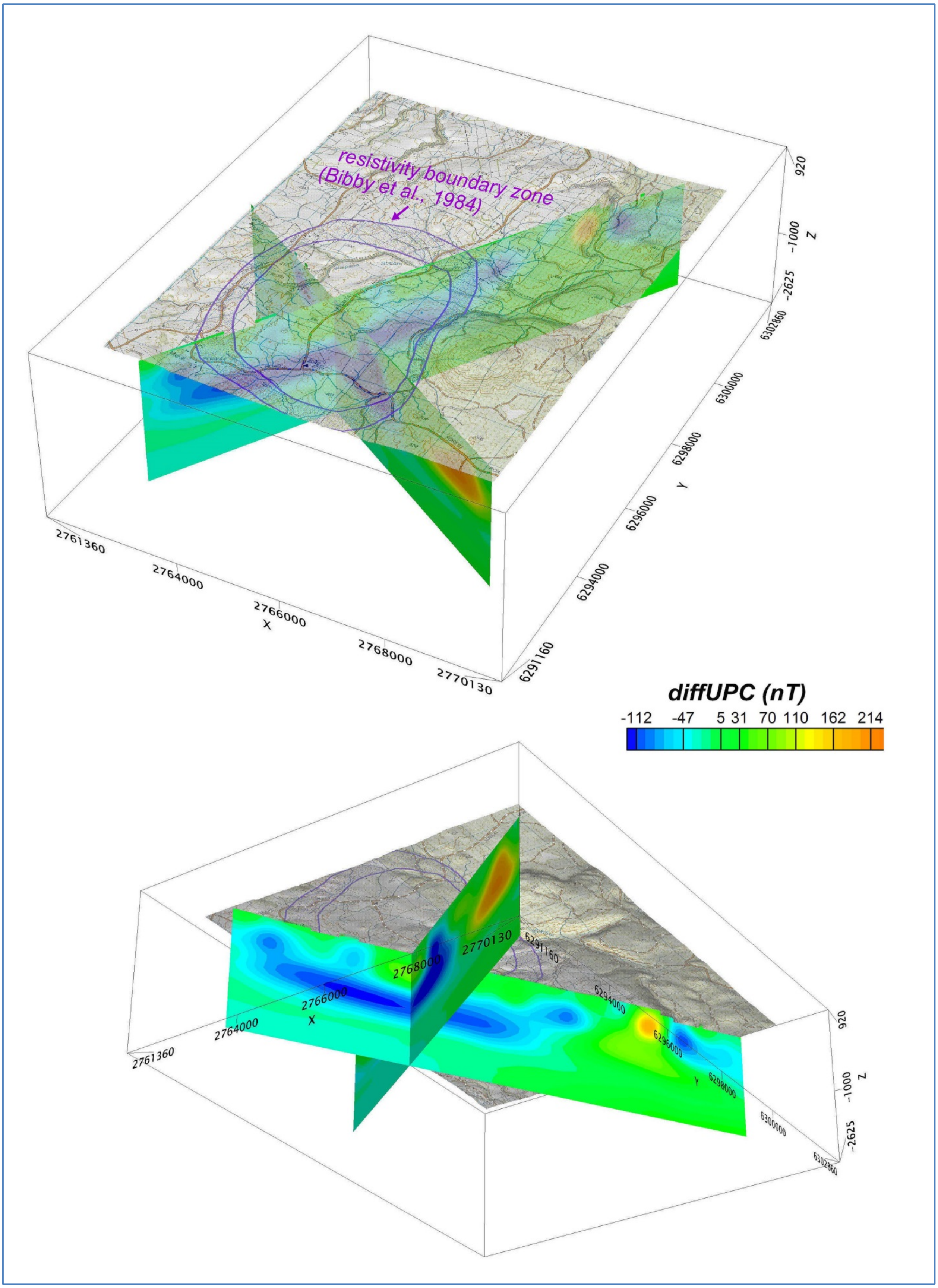


**Figure 3: 3D presentation of the high resolution airborne magnetic data imaging of the study area marked in Figure 1.**

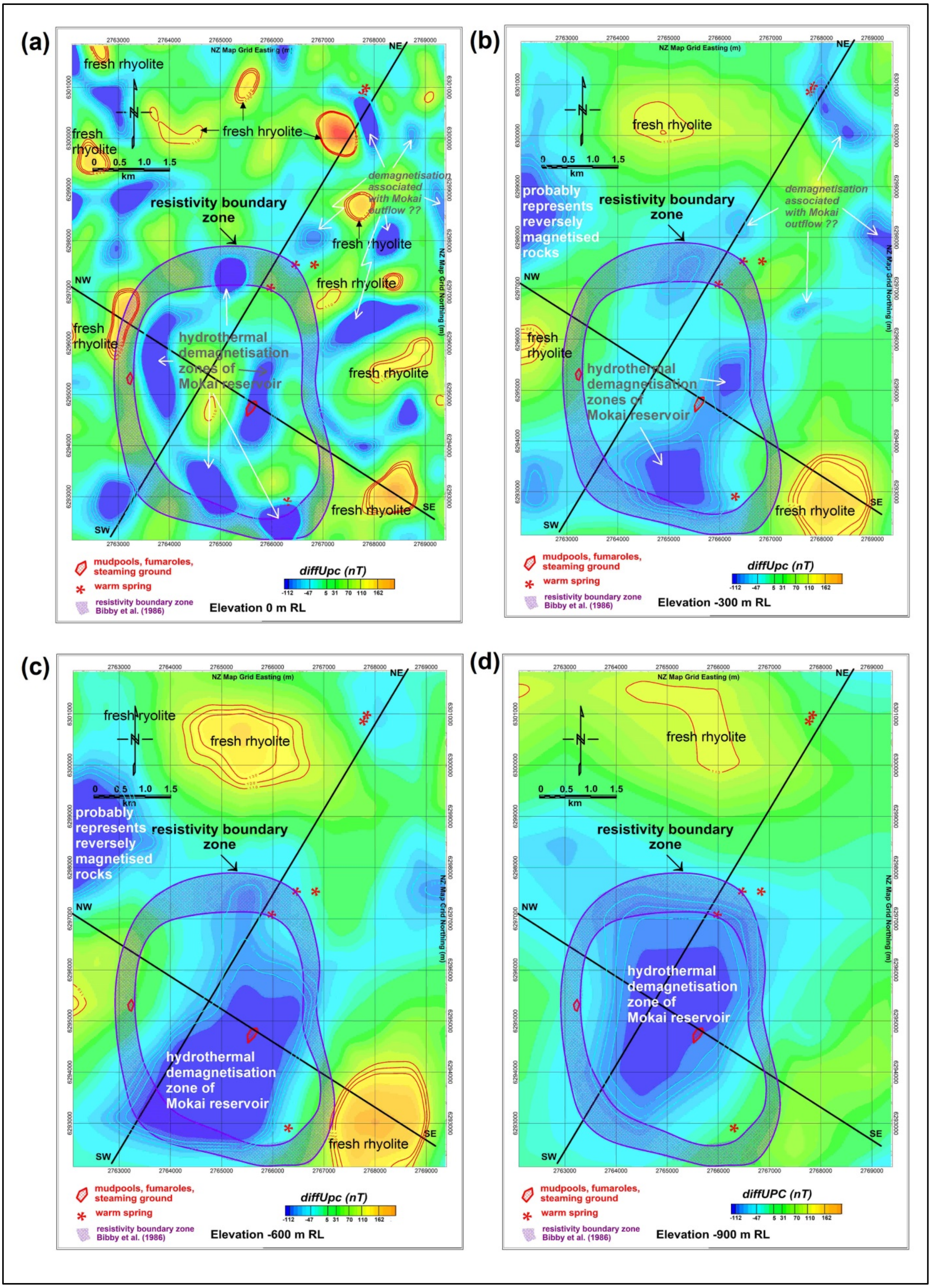


**Figure 4: Maps of *diff UPC* magnetic anomalies across the Mokai Geothermal Field at (a) 0 m RL; (b) -300 m RL; (c) -600m RL; and (d) -600 m RL.**

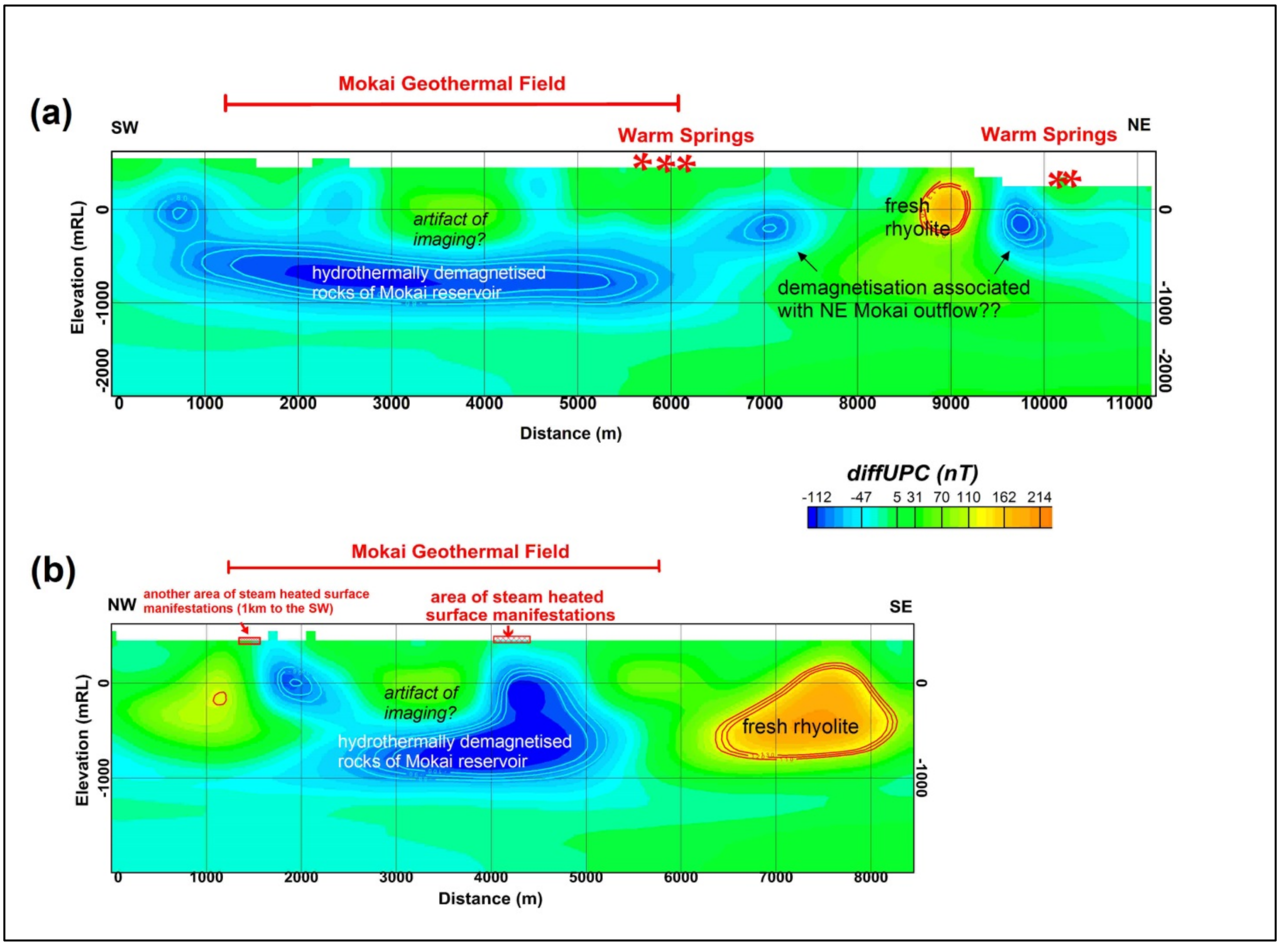


**Figure 5: (a) SW-NE and (b) NW-SE cross sections of 3D images of the Mokai Geothermal Field (see Figure 4 for the cross section locations).**

## 4. DISCUSSIONS

The results shown in Figures 3, 4 and 5 suggest that hydrothermally demagnetised rocks as indicated by low values of *diff UPC* at Mokai are consistent with, but not exactly matching, the resistivity boundary indicated by the Schlumberger resistivity mapping presented by Bibby et al. (1984).

The Mokai hydrothermally demagnetised zone is also thicker (extending down to about -1,000 m RL) than suggested by the previous 3D forward (only extending down to -500 m RL) (Soengkono, 1985).

The -1000 m RL base of hydrothermal demagnetisation zone shown in Figures 5a and 5b are not necessarily the base limit of the reservoir. However they do reflects the maximum depths where the physical and chemical conditions still allow the alteration of ferromagnetic minerals (magnetite and titanomagnetite) by the circulating geothermal fluids into non-magnetic iron sulfide (pyrite).

The results in Figure 5 also suggest that the upper part of the hydrothermally demagnetised zone at Mokai is not flat as suggested by Soengkono (1985). Figure 5b indicates a correlation between two upward extensions of hydrothermal demagnetisation with areas of steam heated surface manifestations. This is a rather interesting result which suggests that hydrothermal demagnetisation can also occur where steam heated acid sulphate fluids interact with the host rocks.

The low values of *diff UPC* at around -300 m RL and -600 m RL shown in Figures 4b and 4c to the northwest and outside the Mokai resistivity boundary probably represents reversely magnetised rocks (older than 780 ka). About 6.5 km further to the northwest, reversely magnetised rocks are exposed as the Kaahu rhyolite lava (Soengkono et al., 1992). Data from the early Mokai drill holes (Wood, 1982; 1983 and 1984) show that inside the Mokai Geothermal field the ignimbrite formations to at least -1,000 m RL are younger than 780 ka. Hence, the existence of low *diff UPC* zone northwest of Mokai, if it indeed represents reversely magnetised rocks, could lead to a speculation that the whole volcanic rocks within the Mokai field have been displaced vertically (down faulted?) by at least 700 m.

The relationship between the hydrothermally demagnetised zone and the productive parts of Mokai reservoir are not analysed as the zones of actual fluid production from the Mokai Geothermal Field are not available for this study, The result in Figures 4a and 4b shows zones of low *diffUPC* that could be associated with the NE outflow of geothermal fluid indicated by the result of Schlumberger resistivity survey (see Figure 1). This result, if true, is also very interesting. It suggests that the outflow of geothermal fluid can hydrothermally alter and demagnetise the host volcanic rocks.

The 3D imaging of the high resolution airborne magnetic anomalies over Mokai area also detects concealed fresh rhyolite domes outside the Mokai reservoir (Figures 4 and 5).

A detailed 3D forward modeling based on the result presented in Figures 3, 4 and 5 would check and correct the possibility of *artifact of imaging* indicates in Figure 5, and provide more detailed information on the magnetisations within the demagnetised region. Hence, the 3D modelling could provide estimation of intensity of the water-rock interaction. Such a 3D modelling was not carried out in this study because of time limitation.

## 5. CONLUSIONS

1. This work has shown that 3D imaging of magnetic anomalies using reduction to pole (RTP) and progressive upward and downward continuations gives a reasonably good result over the Mokai Geothermal Field.

2. The result indicates that hydrothermal demagnetisation at Mokai Geothermal Field is extending down to about -1,000 m RL. However, this level does not necessarily reflect the base of Mokai geothermal reservoir. It merely reflects the maximum depths where the physical and chemical conditions still allow the circulating geothermal fluids to alter iron oxide magnetic minerals (magnetite and titanomagnetite) into non-magnetic iron sulfide mineral (pyrite).

3 The result also suggests that hydrothermal demagnetisation can also be associated with steam heated geothermal fluids.

4. Detailed 3D forward modelling based on the 3D imaging of high resolution airborne magnetic data could reveal the pattern of hydrothermal demagnetisation intensity and, hence, the estimate intensity of water-rock interaction.

5. The relationship between hydrothermal demagnetisation and the likely production of the geothermal reservoir might be analysed by comparing the result of the 3D magnetic imaging and the actual production zones of Mokai reservoir.

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