STRUCTURAL AND HYDROTHERMAL INFERENCES FROM A MAGNETOTELLURIC SURVEY ACROSS MT. RUAPEHU, NEW ZEALAND

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SUMMARY – Magnetotelluric measurements made at 27 sites on and around Mt. Ruapehu, analysed using the phase tensor technique of Caldwell et al. (2004), clearly show that the electrical conductivity structure associated with the volcano is 3-dimensional. Limited 1 and 2-D modelling of the high frequency data show a shallow conductor beneath the eastern part of the volcanic massif which is probably the result of wet volcanic debris rather than from the existence of Tertiary sediments beneath the Tongariro Volcanic Centre. A near surface conductor identified at a single site on the summit plateau is inferred to be connected with the hydrothermal system associated with the Crater Lake. No traces of subsurface outflow from the hydrothermal system were detected within the limited cover provided by this survey.

1. INTRODUCTION

Mt. Ruapehu is a large complex andesitic strato-volcano with a single active crater that in quiescent phases is filled by an acidic lake. The crater has a pattern of intermittent hydrothermal-magmatic eruptions. Violent phreatic eruptions occurred in 1947, 1969, 1971, 1975 and most recently in 1995 and 1996. Andesites, pyroclastics and pumice sequences form a large part of the surface geology of Mt. Ruapehu and the wider Tongariro Volcanic Centre (TVC). However, the deeper structure beneath the TVC is still a subject of debate. A shallow seismic refraction survey to the southeast of Ruapehu (Sissons & Dibble, 1981) indicated velocities compatible with Tertiary sediments at a depth of about 500 m and suggested that these were, in turn, underlain by greywacke at nearly 1300 m depth. Latter (1981) analysed the structure of Ruapehu using volcanic earthquakes and presented a structural model that incorporated both tertiary sediments and greywacke.

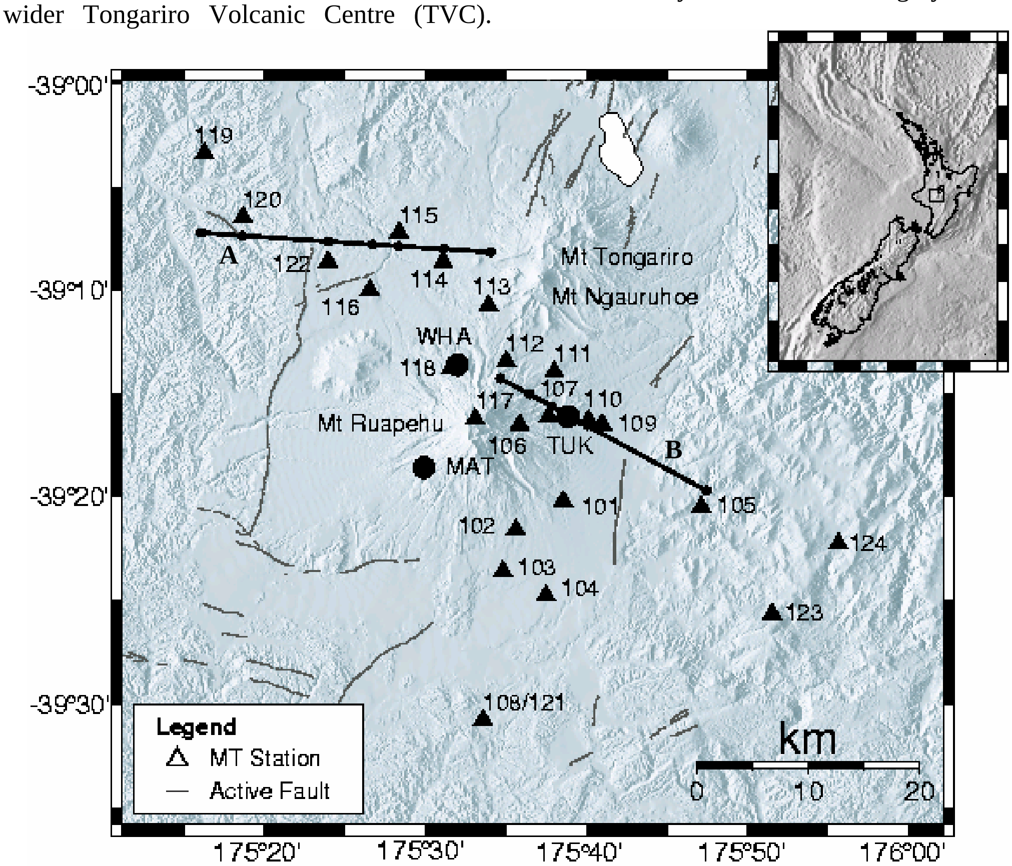

Fig. 1: MT measurement sites - triangles, this study; circles, Hanekop (2002). A and B refer to profiles used in 2-D modelling as discussed in the text.

Nevertheless, despite these results there is no conclusive evidence of either Tertiary sediments or greywacke beneath the TVC. Similarly little is known about the extent of the hydrothermal system associated with Crater Lake or the extent of subsurface outflow from the lake.

Electrical methods have been widely used in the detection and delineation of hydrothermal and magmatic systems associated with volcanoes (e.g. Hoffman-Rothe et al,, 1998; Ogawa et al., 1998; Matsushima et al., 2001; Manzella et al., 2004). Hot or molten bodies are usually identified by extremely low resistivity (Hermance and Colp, 1982). Tertiary sediments have similarly been identified by their low resistivity (e.g. Ingham et al., 2001). Therefore, with the primary aim of both investigating the deep structure beneath the TVC and identifying any electrically conductive features associated with the volcanic structure of Mt. Ruapehu and its associated hydrothermal system, a magnetotelluric (MT) survey of the mountain was conducted in early 2004. 24 MT sites were occupied and these data were combined with earlier long period data collected by Hanekop (2002) at 3 additional locations. Sites were located not only on and immediately around the volcano, but also more widely outside the TVC. Site locations and profile lines discussed below are shown in Fig. 1.

A secondary aim of the study was to test the application of a new method of analysis for MT data. Analysis of data dimensionality using the MT phase tensor (Caldwell et al., 2004) has been used together with a distortion stripping technique developed by Bibby et al. (2004) to remove the

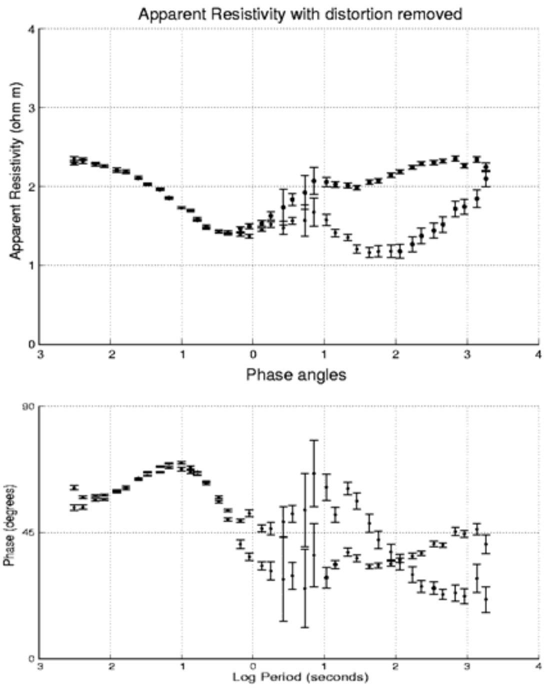

Fig. 2: Example of MT data (site 106) after distortion removal.

effects of distortion from the observed data. This new method does not require the regional 2-D assumption that is inherent in most other distortion removal techniques. Spatial plots of the phase tensor ellipses provide a quick and easy technique for visualising the influence of the dominant conductivity structures and indicate the preferred flow directions of the induced currents.

2. RESULTS

Following the removal of static shift, apparent resistivity and phase curves were plotted for each measurement site. At high frequencies results from sites on the eastern flank of the volcano are very consistent, indicating the existence of a surface resistor overlying a conductor. Beneath the conductor the resistivity again increases. An example of this is shown in Fig. 2. The subsurface conductor to the east appears to be confined to the flanks of the TVC and is absent from the eastern most soundings.

In the method of Caldwell et al. (2004) the phase information contained in the impedance tensor is represented in the form of a tensor - the phase tensor. The phase tensor has the advantage that it is independent of any galvanic distortion and thus represents the (undistorted) response of the regional structures. It also provides a measure of dimension of that regional structure. The MT phase tensor can be represented as an ellipse. The size of the ellipse is inversely proportional to the resistivity gradient. Ellipticity, skew, strike and the direction of current flow are also calculated. The direction of the long axis of the ellipse indicates the direction of preferred current flow while the ellipticity and skew values give information about the dimensionality of the electrical structure at the site. For example, if the skew (β) is such that $|\beta| < \beta_c$ and is accompanied by an ellipticity lower than a threshold value, set here as 0.15, it may be assumed that the structure beneath the site is 1-D. If the ellipticity is significantly non-zero but the skew value still satisfies $|\beta| < \beta_c$, then a 2-D structure is indicated with a strike angle given by the calculated strike direction. If $|\beta| > \beta_c$ then the structure is 3-D. For this study β_c was set to be 3^o. By plotting all the ellipses for a given frequency on a map (as is shown in Figs. 3 and 4) a spatial representation of the variation in dimensionality and strike between data at different sites is obtained. For example, across a boundary at which there is a significant contrast in electrical conductivity the long axis of the phase tensor ellipse will rotate by 90°, being parallel to the boundary on the conductive side.

At high frequencies (e.g. Fig. 3) many of the phase tensor ellipses are nearly circular indicating that the near surface structure is 1-D. Where the ellipticity is significantly non-zero the orientations of the ellipses show little uniformity, reflecting the dominance of local structural effects. However, as the frequency decreases the complete series of ellipse maps begin to show alignment of ellipses between neighbouring sites although significant differences still exist in the direction of ellipses for different groups of sites.

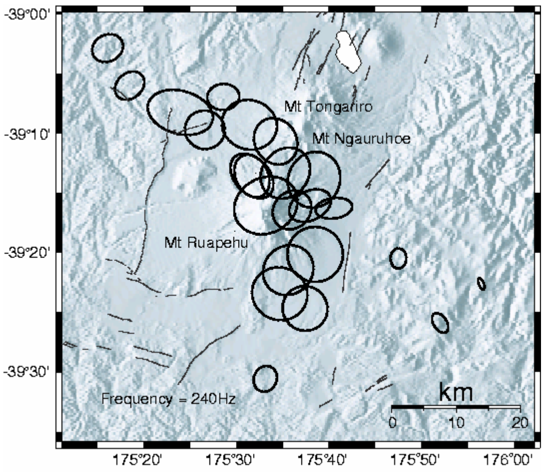

Fig. 3: Phase tensor ellipses for frequency 240 Hz.

Alignments of ellipses are illustrated in Fig. 4 where there is strong NE-SW alignment of ellipses at sites on the east/northeast flank of Mt. Ruapehu. However, at sites both to the northwest and to the south/southeast of the volcano consistent alignments occur in different orientations suggesting a major change in the electrical structure, possibly associated with the edges of the volcanic depression (rift) within which the volcanoes of the TVC lie.

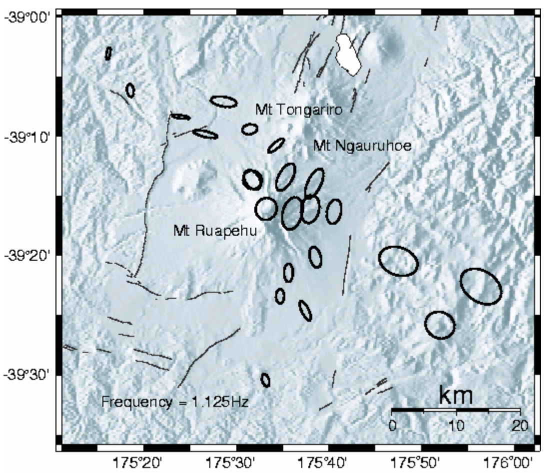

Fig. 4: Phase tensor ellipses for frequency 1.125 Hz.

As the period continues to increase (to 1000s) all the ellipses rotate so that the long axis points very consistently in an approximately NW-SE orientation. This is an indication that at long periods the data respond to regional structure and not structure associated with the volcano.

Detailed analysis of the phase tensor ellipses indicates that, beyond the surficial layering, the dimensionality of the area is predominately 3-D. The uneven distribution of sites around the volcano is not, however, ideal for 3-D modelling. Therefore, at present, modelling has been restricted to those sites and frequencies at which the ellipticity and skew indicate that the structure is 1 or 2-D.

3. MODELS

As a first step in modelling a set of 1-D models was generated. Due to the limited extent of data exhibiting true 1-dimensionality, as indicated by the ellipticity and skew parameters, the determinant of the impedance tensor was used to calculate the apparent resistivity and phase values that were modelled. The determinant impedance is 1-D in the sense that it does not depend upon the orientation of the measurement axes. It has frequently been used as indicator of the manner in which structure varies with depth, even in non 1-D situations. The determinant parameters were modelled using the IPI_MT code (Bobachev 1990). The main result of the 1-D modelling was the identification of the depth to the underlying conductor which is evident in the apparent resistivity curves for sites on the flanks of the volcano. A contour plot of the height above mean sea level of the top of the conductor is shown in Fig. 5. Only sites at which the conductor can be positively identified are included. It is apparent that on the eastern side of Mt. Ruapehu the upper surface of the conductive layer is essentially flat.

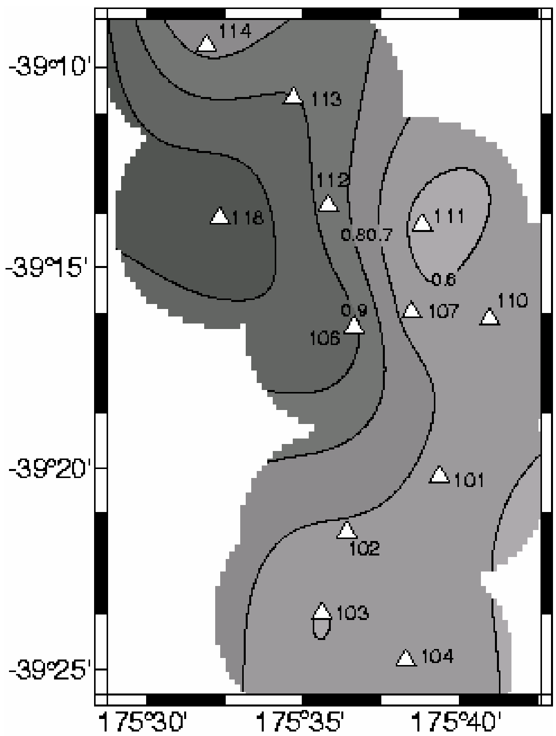

Fig. 5: Height above sea level, in km, of the upper surface of the low resistivity layer at sites to the E and N of Mt. Ruapehu.

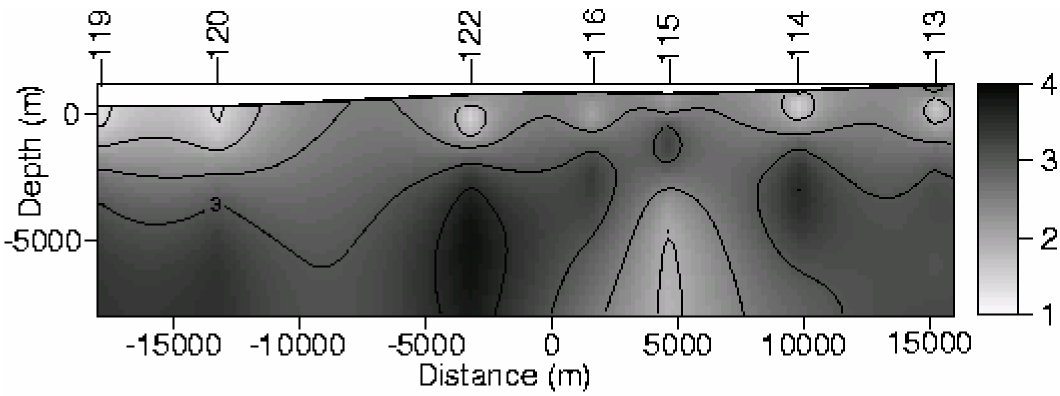

Fig. 6: 2-D resistivity model derived by inversion of data from Profile A shown in Fig. 1. Scale bar and contours are in terms of $\log_{10} \rho$.

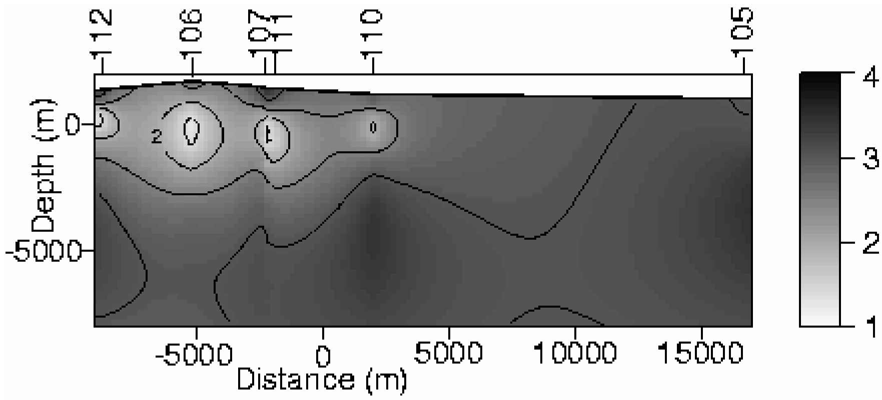

Fig. 7: 2-D resistivity model derived by inversion of data from Profile B shown in Fig. 1. Scale bar and contours are in terms of $\log_{10} \rho$.

However, closer to the volcano this surface appears to dome upwards to a higher elevation. Typical values of resistivity derived for the conductor are in the range 10-30 Ωm. Although the conductive layer could be consistent with either the existence of Tertiary sediments extending beneath the volcano (Latter, 1981; Sissons and Dibble, 1981; Horspool, 2003) or with high porosity volcanic debris (Zeng, 1996), the resistivity values would suggest that the latter interpretation is more likely. The single site measured on the summit plateau of the volcano is vastly different and shows a highly conductive zone at shallow depth. The resistivity of this zone, as indicated by 1-D modelling, is lower than elsewhere and lies in the range more commonly associated with geothermal ground. The conductor seen at the summit is therefore most likely to be associated with the hot acidic Crater Lake and vent system. However, its lateral extent cannot be determined from the measured data.

From the phase tensor analysis two regions of the study area appear to have data which are suitable for modelling in terms of a 2-D conductivity structure over a limited frequency range. The two profiles (A and B) are marked in Fig. 1.

To the west, profile A crosses the TVC boundary just to the north of the Waimarino Fault. The derived 2-D model (Fig. 6) does not show any direct evidence of the fault although a boundary of some nature does appear to exist between sites 116 and 115. This may represent an extension of the eastward splay of the Waimarino Fault. Another interesting feature of this model is the nature of the surface conductor. In the west, beneath sites 119 and 120, the conductor may be confidently identified with the existence of Tertiary sediments. If the conductor indicated by the 1-D modelling was an extension of these it might be reasonably expected to be continuous across the western TVC boundary. A lack of continuity on the other hand would support the hypothesis that the conductive layer on the east and north flanks of the volcano does not in fact result from the existence of Tertiary sediments. The change that occurs near site 115 (Fig. 6) suggests that the conductors are discontinuous, although the relatively large inter-site spacing on profile A means that the apparent discontinuity is poorly resolved. Additional data are required to better resolve this feature.

Profile B, on the eastern side of Mt. Ruapehu, extends from the higher flanks of the volcano across the bounding faults of the TVC onto the greywacke basement outcrops to the east. Consistent with this, the derived 2-D model (Fig. 7) again clearly shows a conductor to be present beneath the eastern slopes of the volcano, and that this does not extend to the east where basement greywacke is known to outcrop. The thickness of the conductor increases to the western end of the profile supporting the conjecture that it may be the result of fractured, wet volcanics, possibly with associated low temperature alteration within the pyroclastic rocks.

4. DISCUSSION

The phase tensor analysis of the MT data clearly indicate that although locally the near surface structure at some measurement sites may be 1-D, the electrical structure associated with Mt. Ruapehu is primarily 3-D in nature. In broad terms this arises because of the different scales of effect of the major factors influencing the MT data. At high frequencies, where the skin-depth is small local 1-dimensionality predominates at many of the sites. With increasing period structure associated with the volcanic massif as a whole starts to have a significant effect, particularly on the data measured at sites close to the mountain itself. At the longest periods more regional structure associated with the tectonic structure of the North Island may have a dominating influence. It is also probable that in areas where significant electrical conductivity contrasts exist, local 2-dimensionality is exhibited over at least some frequency ranges. Examples of this latter effect seem to be associated with the Waimarino Fault and along the eastern margin of the TVC where greywacke outcrops.

1-D modelling of the higher frequency MT data suggests the existence of a conductor beneath the eastern part of Mt. Ruapehu. This conductor appears to be most likely to be associated with wet volcanic debris, rather than Tertiary sediments or outflow from the summit hydrothermal system. 2-D modelling of the present data, although poorly resolved, suggests that this conductor is discontinuous across the western TVC boundary. On the summit of the mountain there is evidence for the existence of a shallow hydrothermal/volcanic system although this survey lacks the resolution to determine the extent of this system. Additional data and 3-D modelling would be necessary to further elucidate the extent of the hydrothermal system and its outflow, or any deeper magmatic system.

Phase tensor analysis has proven to be an effective way of determining the dimensionality of the data and allows for distortion removal in areas where the underlying 2-D assumption is inappropriate. A major benefit of the phase tensor approach is the clear visualisation it provides of which frequencies are influenced by different structures. Frequencies above 100 Hz are strongly influenced by small-scale topography whereas at mid-band frequencies it can be seen that a conductor exists only under the sites beneath the eastern part of the volcano. The orientation of the phase ellipses also indicates conductivity boundaries that may be modelled in 2-D.

Acknowledgements

The authors wish to thank DOC and other landowners for providing access to measurement sites. G. Caldwell and N. Horspool provided invaluable assistance in the field.

5. REFERENCES

Bibby, H., Caldwell, T. & Brown, C., 2004. A co-ordinate invariant approach to distortion effects in magnetotelluric data. Submitted to Geophys. J. Int.

Bobachev, A. A., 1990. IPI2Win, Geoscan –M Ltd, Moscow, Russia

Caldwell, T., Bibby, H.M. & Brown, C., 2004. The magnetotelluric phase tensor, Geophys. J. Int., 157, 1-13

Hanekop, O., 2002. Magnetotelluric survey at Mt. Ruapehu: electromagnetic measurements as indicator of volcanic activity? Unpublished BSc. Hons. Thesis, Victoria University of Wellington.

Hermance, J. & Colp, J.,1982. Kilauea Iki lava lake: geophysical constraints on its present (1980) physical state. J. Volc. Geotherm. Res, 13, 31-61

Hoffman-Rothe, A.A., Müller, A., Ritter, O. & Haak, V., 1998. Magnetotelluric survey of Merapi volcano and across Java, Indonesia. DGG Mitteilungen, Sonerband III/1998, ISSN 0947-1944, 47-52.

Horspool, N., 2003. Bending stress and faulting linked to the load of Ruapehu volcano. Unpublished Dip. App. Sci. Thesis, Victoria University of Wellington

Ingham, M., Whaler, K. & McKnight, D., 2001. Magnetotelluric sounding of the Hikurangi Margin, New Zealand. Geophys. J. Int., 144, 343-355.

Latter, J., 1981. Volcanic earthquakes and their relationship to eruptions at Ruapehu and Ngauruhoe. New Zealand. J. Volc. Geotherm. Res 9, 292-309

Manzella, A., Volpi, G., Zaja, A. & Meju, M., 2004. Combined TEM-MT investigation of shallow-depth resistivity structure of Mt. Somma Vesuvius. J. Volc. Geotherm. Res., 131, 19-32.

Matsushima, N., Oshima, H., Ogawa, Y., Takakura, S., Satoh, H., Utsugi, M. & Nishida, Y., 2001. Magma prospecting in Usu volcano, Hokkaido, Japan, using magnetotelluric soundings. J. Volc. Geotherm. Res, 109, 263-277.

Ogawa, Y., Matsushima,N., Oshima, H., Takakura, S., Utsugi, M., Hirano, K., Igarashi, M. & Doi, T., 1998. A resistivity cross section of Usu volcano, Hokkaido, Japan, by audiomagnetotelluric soundings. Earth Planets Space, 50, 339-346.

Sissons, B. & Dibble, R., 1981. A seismic refraction experiment southeast of Ruapehu volcano. NZ J. Geol. Geophys., 24, 331-338

Smith, J.T. & Booker, J.R., 1987. Magnetotelluric inversion for minimum structure. Geophysics, 53, 1565-1576

Zeng, Y., 1996. Geophysical investigations of the subsurface of Tongariro Volcanic Centre, New Zealand. Unpublished PhD thesis, Victoria University of Wellington