DEEP ELECTRICAL STRUCTURE BENEATH THE TAUPO VOLCANIC ZONE AND THE SOURCE OF GEOTHERMAL HEAT

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SUMMARY – Electrical resistivity surveys now provide images of the electrical structure beneath the Taupo Volcanic Zone (TVZ) to depths that exceed those of the base of the geothermal systems. Multiple-source bipole-dipole surveys show there are three distinctive zones in the upper crust across the TVZ. Highly conductive basins up to 5 km deep, found on both the east and west sides of the TVZ, are separated by a resistive structure beneath the (cold) Taupo Fault Belt. At greater depths, inversion of magnetotelluric data along a profile crossing the TVZ shows a significant conductive structure at a depth of about 10 km. This conductor may be associated with magma within the crust and hence may represent the ultimate source of geothermal heat.

1. INTRODUCTION

The ultimate source of the geothermal heat discharged through our geothermal systems is magma. There is considerable evidence for magmatic activity beneath the Taupo Volcanic Zone (TVZ) from past volcanism. Over the last 300,000 years magma has been erupted at the surface at an average rate of about 0.3 m^3/sec (Wilson et al. 1995). Prior to an eruption, magma accumulates within the crust. The area of collapse that followed the eruption of 530 km^3 of magma during the Oruanui eruption, for example, suggests that, prior to the eruption, magma accumulated at a depth of 6 km or greater beneath an area of about 200 km^2.

However the average rate at which energy has been brought to the surface by erupted magma is small compared with the 4000 MW of heat discharged through the geothermal systems of the TVZ. If this large geothermal heat flux arises from cooling of magma, it requires the cooling of about 1 m^3/sec of molten rock, or three times the known rate of magma eruption at the surface. Thus, the high observed geothermal heat flux suggests that a large part of magmatic material entering the system does not reach the surface but is intruded into the base of the crust beneath the TVZ where it is cooled by circulating geothermal waters (Bibby et al. 1995). The nature of the magmatic heat source and the process by which the heat is transferred from the magma to the geothermal waters are poorly understood aspects of our geothermal systems.

Several geophysical techniques are available to image deep structures in the TVZ. Traditionally seismic reflection techniques have been used but they have been largely ineffective because of severe reverberation that occurs within the shallow volcanic layers. Electrical techniques have been very successful for detecting and delineating high-temperature near-surface geothermal resources. To probe deeper into the crust requires application of several complementary techniques and a good knowledge of the near-surface geology and resistivity structure. Recently, a series of studies has been made to examine the electrical structure beneath the TVZ at successively greater depths. Multiple-source bipole-dipole techniques have been able to image structures to 5-7 km (e.g. Risk et al., 1999). In turn, these images can provide constraints for the interpretation of magnetotelluric (MT) surveying which can probe to much greater depths

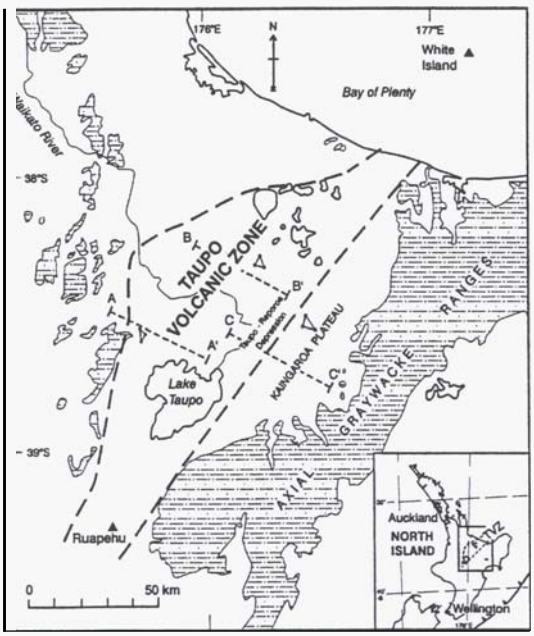


Figure 1. ***Location of the three bipole-dipole surveys which have been used to obtain an electrical cross section through the TVZ. The locations of the current sources are shown as the solid triangle.***

(Ogawa et al. 1999, Ingham 1999). We report here a summary of results from recent studies using both techniques.

2. MULTIPLE-SOURCE BIPOLE-DIPOLE SURVEYS

A series of deep penetration dc resistivity surveys has been made across the TVZ using the multiple-source bipole-dipole method (Risk et al., 1970, 1993). Each survey uses three bipole current sources (ca. 3-5 km long) made up by using combinations of three grounded electrodes. During a survey the current source is kept at the same location while measurements of electric field strength are made in the region of interest. Measurement sites can be up to 35 km fiom the source. The use of three source bipoles provides current fields in three different directions at the field sites. A full description of the measurement technique can be found in Risk et al. (1999) and the analysis of the data in terms of apparent resistivity tensors is given in Bibby (1986).

The locations of the current sources and field sites for the three multiple-source bipole-dipole surveys discussed in this paper are shown in Fig. 1. The measurement sites make up a transect that crosses the full width of the TVZ and is approximately perpendicular to the strike of many key features. For the eastern and western surveys, current electrodes were placed in surficial ignimbrites which overlie the shallow resistive greywacke basement (≈300 Ωm), and for the central survey they were sited in a high-resistivity region that had been identified fiom earlier Schlumberger array surveys. Measurement sites were chosen to avoid the influence of the very low resistivity zones associated with the geothermal fields.

To facilitate analysis, the field measurements are converted into apparent resistivity tensors.

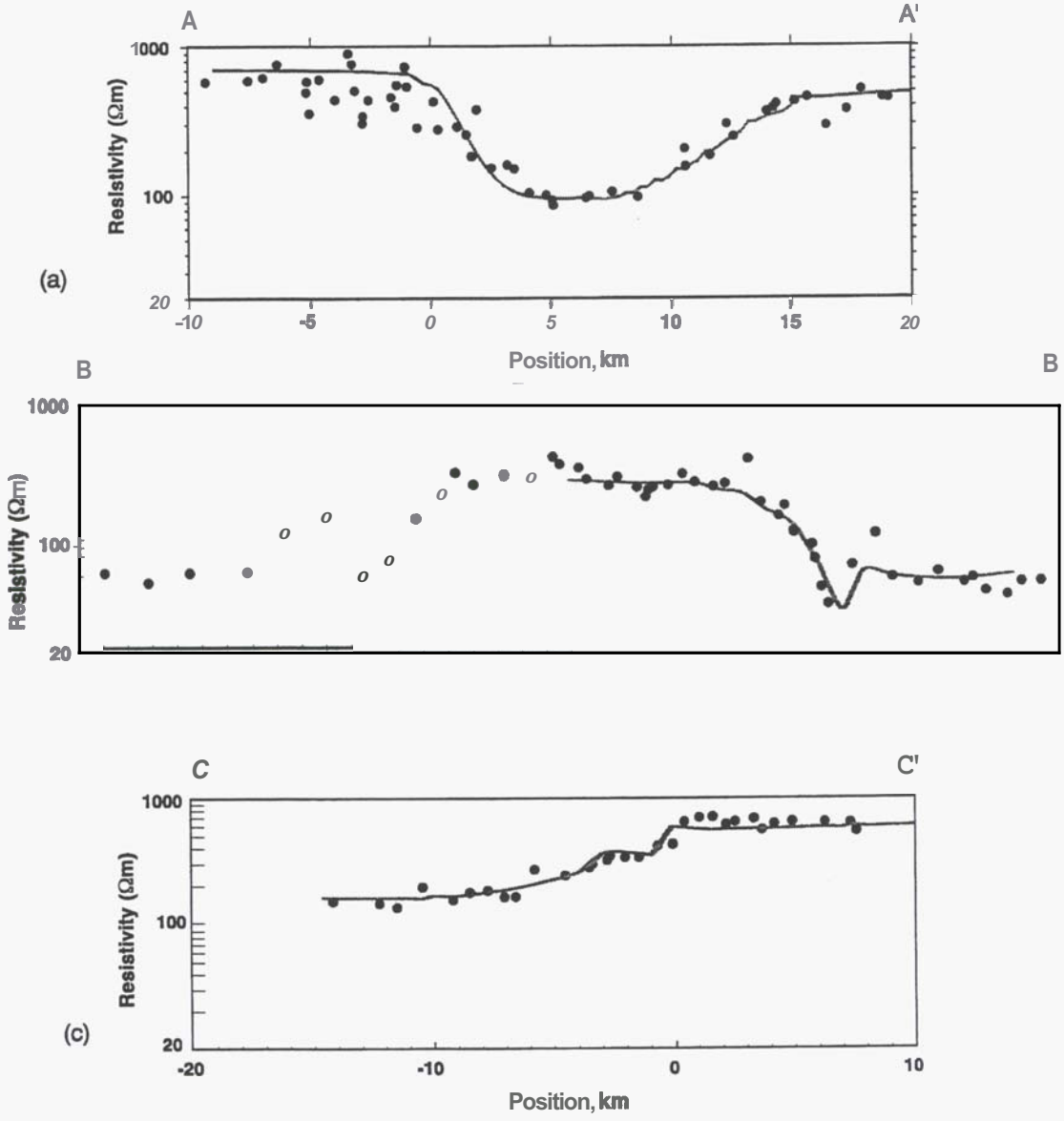


Figure 2. *The measured bipole-dipole resistivity data along profiles (shown in Fig. 1) lying to the west, centre and east of the TVZ. Solid line shows the results derived using the models of Fig 3a,b,c.*

Detailed discussion of resistivity tensors and their representation as apparent resistivity ellipses can be found elsewhere (Risk et al. 1999, Bibby et al. 1998). Only the key features of the interpretation are presented here. For modelling purposes, the tensor invariant related to the determinant (P_2) has been used. The values of P_2 along the three profiles of Fig. 1 are shown in Figs. 2a,b,c.

Both the regional apparent resistivity pattern (e.g. Risk et al., 1999) and the topography suggest that the near-surface structure in the TVZ is predominantly two-dimensional. Smaller-scale three-dimensional features such as geothermal systems are superimposed on this trend. Our interpretations used a two-dimensional finite element forward modelling technique (based on Coggon, 1971) which allows for inclusion of surface topography. For each survey forward modelling was applied iteratively to obtain a match for the P_2 invariant. For this type of survey, inversion can be non-unique, as there can be a trade-off between resistivity and thickness of deep conductive structures (equivalence), so that only the conductance (thickness/resistivity) of the buried structure can be resolved. However, limits can usually be placed on the possible range of viable resistivity values. The models of the crustal resistivity, shown in Figs. 3a,b,c are regarded as the most geologically appropriate model for each of the profiles.

21 Features of the structure

To both east and west, outside the TVZ, the greywacke basement has resistivities of 300 - 1300 Ωm which is high compared to the near-

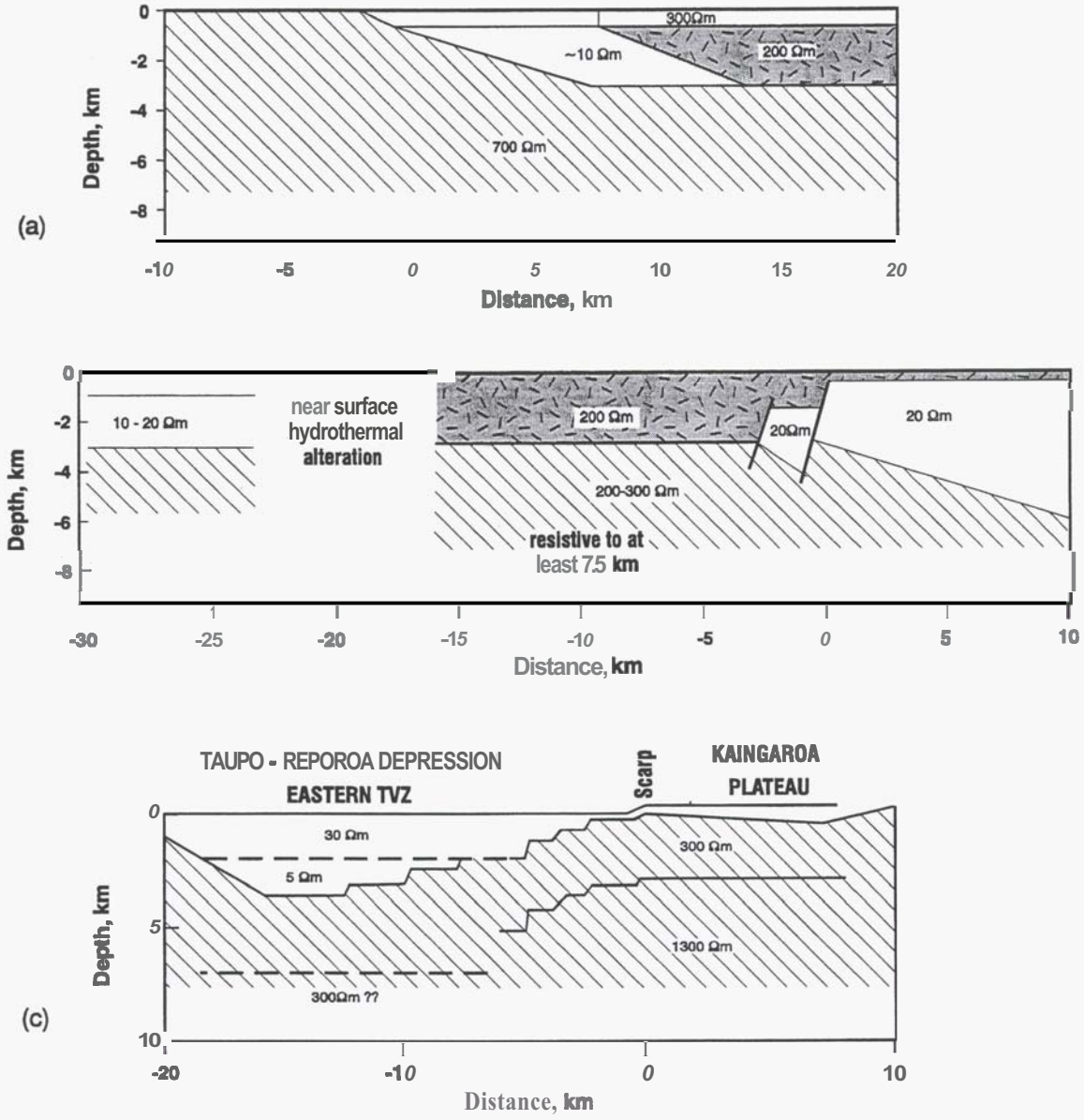


Figure 3. Models *of the electrical resistivity structure beneath the TVZ based on the interpretation of surveys to the west (a), centre (b) and east (c) of the TVZ. Matches between modelled and measured data are shown in Fig 2a,b,c.*

surface resistivities within the TVZ. At both margins, the resistive greywacke is down-faulted towards the TVZ beneath the less resistive volcanics. The down-faulting is also seen as a steep gradient in gravity at the margins. The resistivity models show that the resistive basement is downthrown by at least 4 km.

Within the TVZ the electrical structure suggests three major features: low-resistivity basins on both the eastern and western sides, separated by a central high-resistivity zone. The boundaries between these zones run nearly parallel to the larger-scale NNE trend of the TVZ. The eastern basin (Taupo-Reporoa Depression) extends from the Kaingaroa fault to the Paeroa fault. It is highly conductive at depth, with a width of about 10 km. The basin thins westward to terminate at the Paeroa fault.

Distinct from the near surface low resistivity zones which are directly associated with geothermal activity, the deep low resistivity layers within these basins have been interpreted as low-temperature alteration within older (>1Ma) pyroclastics (Bibby et al. 1999). On the west this conductive material is believed to be a remnant of an early phase of volcanism that has been left relatively undisturbed by later activity within the TVZ. The east side of the TVZ (Fig. 3c) is also characterised by a great thickness of conductive material. In this case the area has been the source region for caldera eruptions in the last one million years. We suggest however that the cause of the conductivity in the basin is similar to that to the west particularly at depths greater than 2 km.

Between these basins, in the central section of the TVZ (the Taupo Fault Belt, TFB, Fig. 4), there is a resistive block of about 15 km wide. The resistive formations (≈ 200 Ωm) within the TFB extend from the surface to depths of at least 7 km (Risk et al., 1999) with no evidence for interbedded low-resistivity layers. The high resistivities found in the TFB (or conversely the absence of any conducting material) is surprising, particularly as this limits the possible age of volcaniclastics in the TFB. The resistive structure is interpreted as young ignimbrites and other volcaniclastic layers overlying a greywacke basement. There can be no old ignimbrites present beneath the TFB. In contrast to the eastern basin, geothermal heat output through the TFB is virtually zero. As a component of the large-scale systems of fluid convection in the TVZ (e.g. Bibby et al., 1995), the Taupo Fault Belt has a role as one of the major recharge areas through which cold meteoric waters enter the convection system. The faulted and fractured racks within the TFB provide permeable paths for the down-flowing meteoric water.

3. MAGNETOTELLURIC MEASUREMENTS

Applied source resistivity techniques are limited in the penetration that can be achieved and thus, to determine structure to greater depths, natural source (MT) techniques are required. In 1998 a set of 20 wide-band MT soundings were measured along a 110 km-long profile approximately perpendicular to the strike of the TVZ (Fig. 4). The profde was chosen close to that of the dc surveys. The measurements were made using two 5-component, wide-band MT systems (Phoenix V5-MT) with synchronized GPS clocks to allow remote referencing (Gamble et al., 1979). At most sites along the profile, data quality was good for periods in the range 0.01 to 1,000 s. However data at 4 sites had to be rejected because of cultural noise (electric fences). Typical site spacing was 10 km but was reduced to 5 km near the eastern margin of the TVZ where rapid lateral resistivity changes were expected. Data were recorded for at least 30 hours at each site.

Analysis of the data using both induction arrows (Parkinson, 1962) and tensor decomposition (Groom and Bailey, 1989) suggest that the structure is approximately two-dimensional with a strike parallel to that of the TVZ. This two-dimensionality is also recognised to the north of the profile of Fig. 4 in MT data gathered by Ingham (1999). Using the strike of the TVZ, the data were decomposed into the traditional TE and TM modes (magnetic field perpendicular and parallel to strike). Details of the decomposition and pseudo-sections are given in Ogawa et al. (1999). Although it is possible to deduce the structure from the sounding curves and the associated pseudo-sections, modelling is required to derive a spatial image of the resistivity structure. The dimensional analysis of the data suggests it is appropriate to use two-dimensional inversion procedures to derive the deep structure.

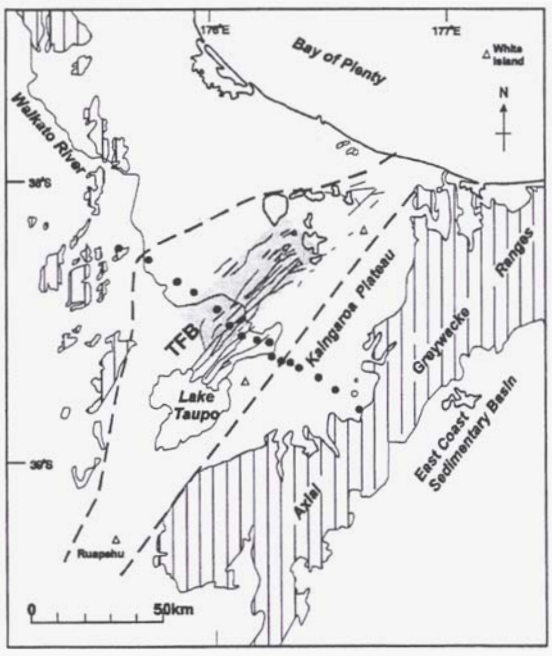


Figure 4. *Map of the TVZ showing the MT measurement sites.*

3.1 Two-dimensional Modelling

The apparent resistivity and phase data from both the TE and TM modes were inverted simultaneously using the inversion code of Ogawa and Uchida, (1996). Within the TVZ the upper 300 m of the initial model was fixed using spatially averaged resistivity values from Schlumberger array mapping (AB/2 = 1,000 m). To the east a thickening layer of 20 Ωm was included to represent the east coast sedimentary basin. Below these features, the initial model had a uniform earth of 100 Ωm. As the station spacing is too great to resolve the near surface structure, data in the period range from 1 s to 1,000 s were used for the inversion. The model derived from the inversion (after 20 iterations, rms error 1.04) is shown in Fig. 5. Analysis of the resolution of the model indicates that both the shallow structure and the upper surface of the deeper conductors are well resolved (Ogawa et al. 1999).

4. RESISTIVITY STRUCTURE BENEATH TVZ

The dc and MT surveys provide successively deeper images. Near the surface, the model obtained from the inversion of the MT survey data shows two conductive anomalies (C1 and C2) separated by a resistive zone (the Taupo Fault Belt). The two conductive basins correspond to the conductive basins imaged in detail by the dc resistivity surveys. On the east side of the TVZ the thickening of the basin westward, corresponding to the faulted greywacke margin, can also be seen on the MT image (Fig. 5). On the west side of the TVZ the dc and MT surveys. do not pass along the same path, but similar basin-like structures can be seen in both surveys. In the case of the MT survey this corresponds to the Mangakino caldera which is somewhat wider than the basin structure seen in the dc survey which passes to the south.

Beneath all three zones of the TVZ, both dc an MT surveys show high resistivities with no indication of a low-resistivity gap that might indicate a rift in the basement greywacke. With its greater penetration, the MT survey shows that this resistive (greywacke?) layer extends to a depth of about 10 km. Thus, our data do not appear to support a rifting model for the origin of the TVZ (Stern, 1985), and suggest instead a near continuous resistive basement beneath the TVZ, consistent with a continuous greywacke basement.

Below the resistive layer (about 10 km deep) the lower crust and upper mantle are unusually conductive. The central and shallowest of these conductors, C3, lies about 10 km deep below the TFB. This conductor appears to be of finite extent with no apparent connection to the slightly deeper conductors on either side (C4 and C5). Strong crustal seismic reflectors, which were observed at about the same depth within the offshore extension of the TVZ in the Bay of Plenty (Davey and Lodolo, 1995), have been interpreted as crustal melt. Both the finite extent of the conductor (C3) and the correlation with the seismic reflector suggest that the conductor may be associated with magma accumulation at depth beneath the TVZ.

At depths greater than about 20 km beneath the central and eastern part of the TVZ resistivities are low (C7, <100 Ωm). The width of this zone is similar to the young TVZ (Wilson et al. 1995), which is defined to be the area enclosing all the volcanism younger than c. 330 ka. The deep low resistivity structure is consistent with a zone of connected melt within the upper mantle.

5. CONCLUSIONS

The results obtained from the deep penetration MT data provide an essential complement to the high resolution image of the upper 5-7 km of the crust obtained from dc resistivity measurements.

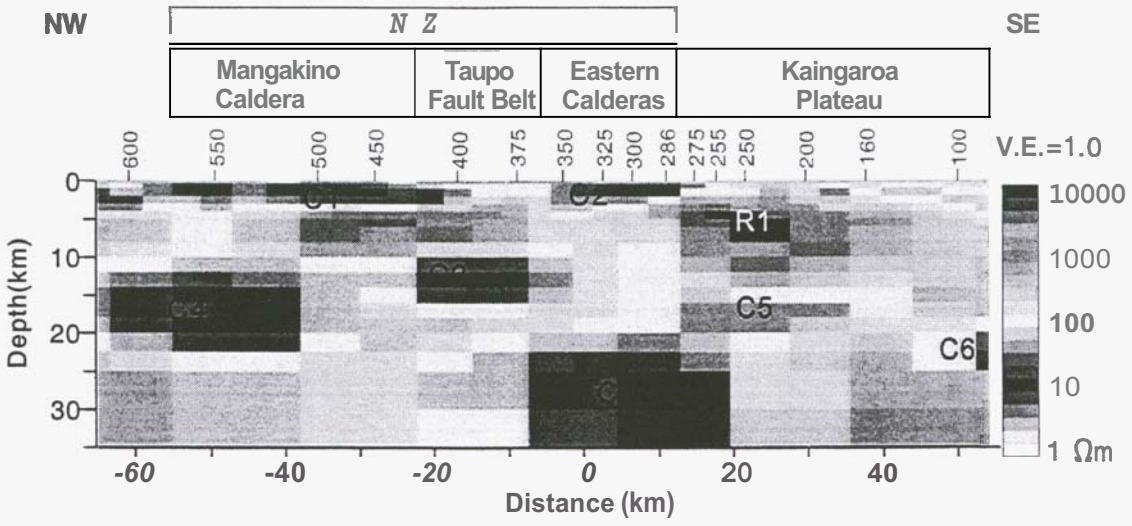


Figure 5. *Model of the deep electrical structure obtained from the inversion of the MT resistivity and phase from both TE and TM modes. Conductive and resistive features are labelled C1-C7 and R1 respectively.*

To obtain good resolution of the near surface requires close spaced measurements that would not be economically viable using MT alone. However the MT data is essential to image the deeper portion of the crust.

The great thickness of conductive material found along the eastern side of the TVZ (Taupo-Reporoa Basin) has considerable implications for geothermal prospecting. The contrast between conductive geothermal fluids found within the geothermal plume and its surroundings is very pronounced near the surface. However the signatures at greater depths will be very much subdued. The resistivity below 2 km in the Taupo-Reporoa Basin could be as low as 5 Ωm, which could be lower than the resistivity associated with the high temperature geothermal plume which must pass through it.

Although only preliminary results have been obtained so far, the identification of a shallow conductive zone only 10 km deep is important. If this is indeed magma at depth it raises a number of questions. It is located beneath the Taupo Fault Belt, which is characterised by low surface heat output. However, it is not observed beneath the eastern side of the TVZ through which most of the geothermal heat is discharged. On the other hand the deeper conductive zone associated with mantle melt does lie beneath the zone of high geothermal discharge. Better resolution of these deep conductivity zones is thus an important target for further work.

6. ACKNOWLEDGEMENT

This paper is GNS Contribution No. 2038. This work has been partially funded by Foundation for Research, Science and Technology.

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