

Misinterpretation of Electrical Resistivity Data in Geothermal Prospecting: a Case Study from the Taupo Volcanic Zone

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ABSTRACT

Perhaps the most successful application of electrical resistivity techniques for delineating geothermal systems has been in the early exploration of the Taupo Volcanic Zone of New Zealand. Systematic mapping using the Schlumberger resistivity arrays with fixed spacings has identified 23 individual geothermal systems with well-defined boundaries. The remarkable success of the method in the Taupo Volcanic Zone is linked to the very thick (500+ metres) cover of young (<500 ka), highly resistive, pyroclastic material that forms the upper layers of the region. However, the success has resulted in a lack of care with interpretation based on the belief that resistivity data can be simply interpreted using the apparent one-to-one correlation between low resistivity and the presence of geothermal fluids. The first example of misinterpretation of electrical data in the Taupo Volcanic Zone was the Horohoro (Matahina) prospect where a deep low resistivity layer was drilled for geothermal fluids in 1987 despite warnings of possible misinterpretation. This well was cold and the cause of the low resistivity has now been established as old ignimbrite layers (>1 Ma) which have undergone low-temperature diagenetic alteration to form highly conductive, connected clay paths within the rock matrix. The older, conductive ignimbrites are extensive and continuous around the edges of the TVZ where they are underlain by resistive basement rocks. Within the TVZ, structural investigations using magnetotelluric show these conductors to be present at depth beneath much of the area. We outline here both the history and the lessons of the past, in the hope that they will provide guidance for future geothermal explorations.

1. INTRODUCTION

Electrical resistivity prospecting techniques have been very successful for determining the shallow extent of geothermal systems within New Zealand's Taupo Volcanic Zone (TVZ) (Fig. 1). Mapping of electrical resistivity (e.g. Bibby, 1988; Stagpoole and Bibby, 1998b) shows that all known geothermal features in the TVZ can be linked to an associated low-resistivity zone. The extent of the major geothermal fields in the TVZ can be very accurately defined using the large resistivity contrast between the highly conductive material within the geothermal fields and the resistive cold-water saturated volcanic rocks that surround the fields. The converse, however, is not true. Low resistivity does not necessarily indicate geothermal conditions.

The causes of the low resistivities within geothermal reservoirs are well known (e.g. Bibby *et al.*, 1995). Geothermal waters have high concentrations of dissolved salts which provide conducting electrolytes within a conductive rock matrix; the conductivities of both the

electrolytes and the rock matrix are temperature dependent in a manner that causes a large reduction of the bulk resistivity with increasing temperature. Possibly the most important factor affecting rock resistivity is alteration of the rock matrix caused by prolonged exposure to high-temperature waters. The alteration products greatly reduce the resistivity of the rock matrix (Caldwell *et al.*, 1986). Furthermore, low temperature (<c. 150°C) alteration species (illite-smectite) are significantly more conductive than the higher temperature (chlorite) species (Björnsson *et al.*, 1986). Thus, an increase in resistivity beneath a highly conductive surficial layer, reflecting an increase in temperature with depth, is a common signature of high temperature geothermal systems. This characteristic resistivity increase is seen within most geothermal systems of the TVZ and is clearly demonstrated by the Schlumberger mapping (eg. Stagpoole and Bibby, 1998a).

There is another factor that contributes to the success of resistivity techniques in the TVZ. The upper kilometre or so of the TVZ comprises young (< 330 ka) volcanic rocks which (away from the geothermal fields) have resistivities greater than 100 Ω m. It is the large contrast between the conductive rocks within the geothermal systems and the surrounding young volcanics that allows the shallow boundaries of the geothermal systems to be clearly defined. However, the resistivity contrast between a geothermal reservoir and its surroundings is reduced considerably at depth (Risk *et al.*, 1993).

The overwhelming success of resistivity mapping for geothermal prospecting has led to a lack of care in the interpretation of resistivity data. In 1986 a geothermal drillhole was sited on a zone of deep low resistivity on the western side of the TVZ. This hole was one of the last to be drilled in the New Zealand government funded geothermal exploration program of that era. The hole (Horohoro 1) was cold. Shortly after the completion of this well, government funding ceased and geothermal exploration went into abeyance until recently. In the last two years, with the increased quest for indigenous sources of energy, there has been a revived interest in geothermal energy within New Zealand. In the renewed exploration program the emphasis has moved from the DC resistivity measurement techniques, used with success in the past, to magnetotelluric (MT) methods which have now become the exploration method of choice. The MT method provides information on resistivity variations to very much greater depths than those achieved in the earlier surveys. With increased penetration, the influence of older conductive strata becomes increasingly significant and thus complicates interpretation. With the increased interest in geothermal developments in New Zealand it is appropriate to examine the reasons for the failure of the Horohoro well in the hope that the mistakes of the past will provide guidance for the current phase of geothermal development in New Zealand.

2. ELECTRICAL MAPPING OF THE TVZ

All but one of New Zealand's high-temperature geothermal systems lies within the Taupo Volcanic Zone. Electrical Mapping of the TVZ for the purposes of geothermal exploration was started in the early 1960s following experiments which proved the method's effectiveness (Hatherton *et al.* 1966). Initially, a Wenner electrode array was used but this was soon replaced by Schlumberger array measurements using the equivalent electrode spacings. The depth of penetration, which is a function of the array spacing, was chosen carefully. It was observed that the greatest contrast in electrical properties across the boundary

of a selection of geothermal systems was obtained using the array spacing (denoted by $AB/2$, the distance from the array centre to the current electrodes) of about 500 m. The mapping that continued until about 1985 followed the template established by these early experiments and used Schlumberger array measurements with (nominal) array spacings ($AB/2$) of 500 m and 1000 m. A description of the mapping techniques and the quality control on these surveys are given in Bibby (1988). There are now about 20,000 individual measurements which together cover virtually the entire TVZ. The resulting electrical resistivity maps (Fig. 1; Bibby *et al.* 1995, Stagpoole and Bibby 1998b) show a remarkably consistent pattern.

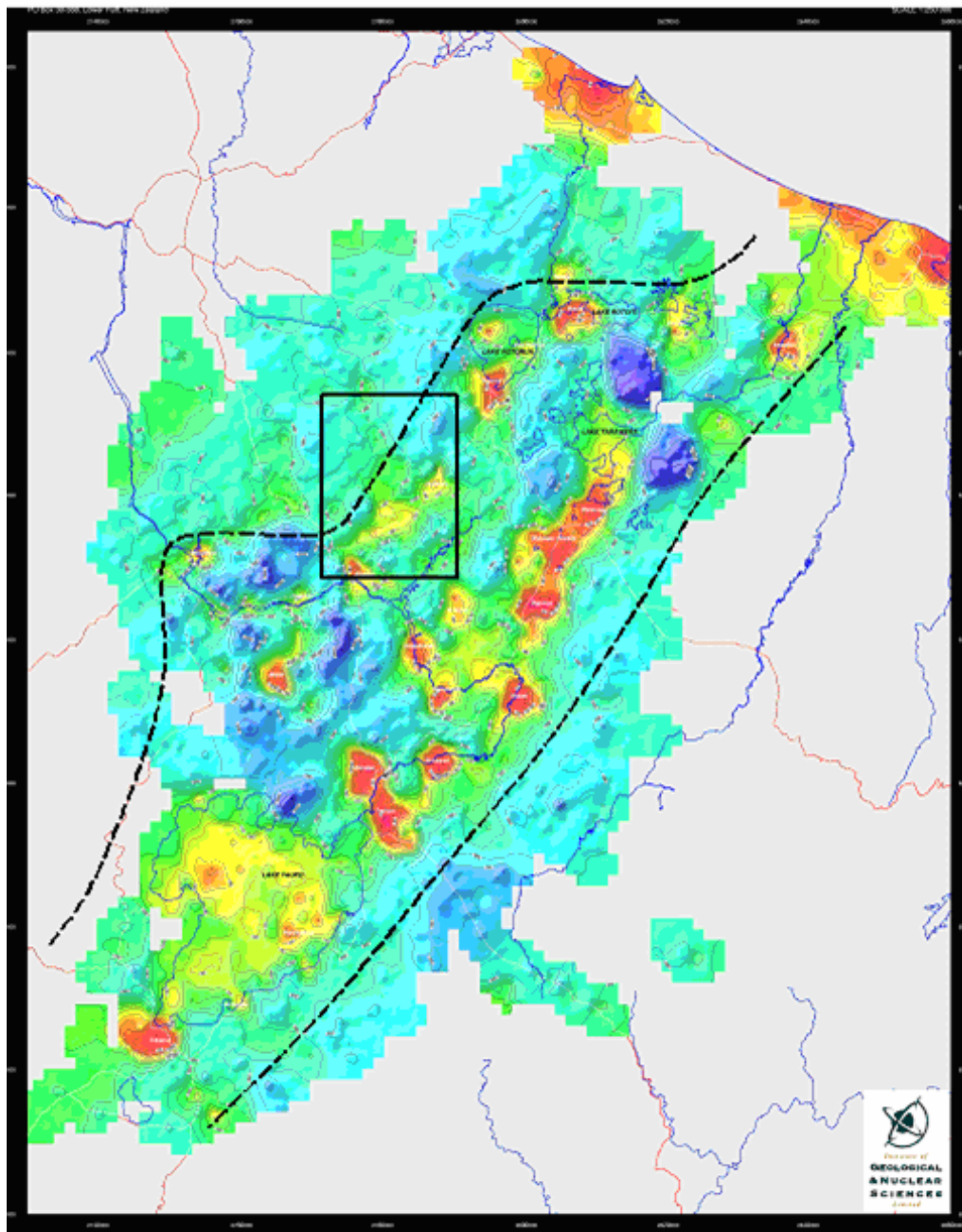


Figure 1: Electrical resistivity map of the Taupo Volcanic Zone. Contours are based on about 12,000 individual measurements made with a Schlumberger array with nominal array spacing ($AB/2$) of 500 m. With the exception of the areas on the coast, the areas shown in red (indicating apparent resistivity $< 10 \Omega m$) outline the known high temperature geothermal systems. For this map there is a very close correlation between the low resistivity areas and the occurrence of geothermal fields. The dotted curves mark the outline of the TVZ. The area of Fig. 2 is outlined by the rectangle.

For the apparent resistivities measured with AB/2 of 500 m there is a clear relationship between the well defined low-resistivity zones (Fig. 1), which are typically about 4 km in diameter, and the occurrence of high temperature geothermal features. The success of this very simple technique was remarkable. Apart from a region near the coast (Fig. 1) there is an apparent one-to-one correlation between the low resistivity zones defined by the mapping

and the known geothermal features. Altogether 23 high temperature geothermal systems were outlined (Bibby *et al.* 1995). However this one-to-one correlation starts to break down when the deeper penetration resistivity measurements are used. The pattern obtained using the deeper penetration (AB/2 of 1000 m) mapping highlighted other low-resistivity zones which are not geothermal in origin. This is well demonstrated by the surveys and drilling at Horohoro.

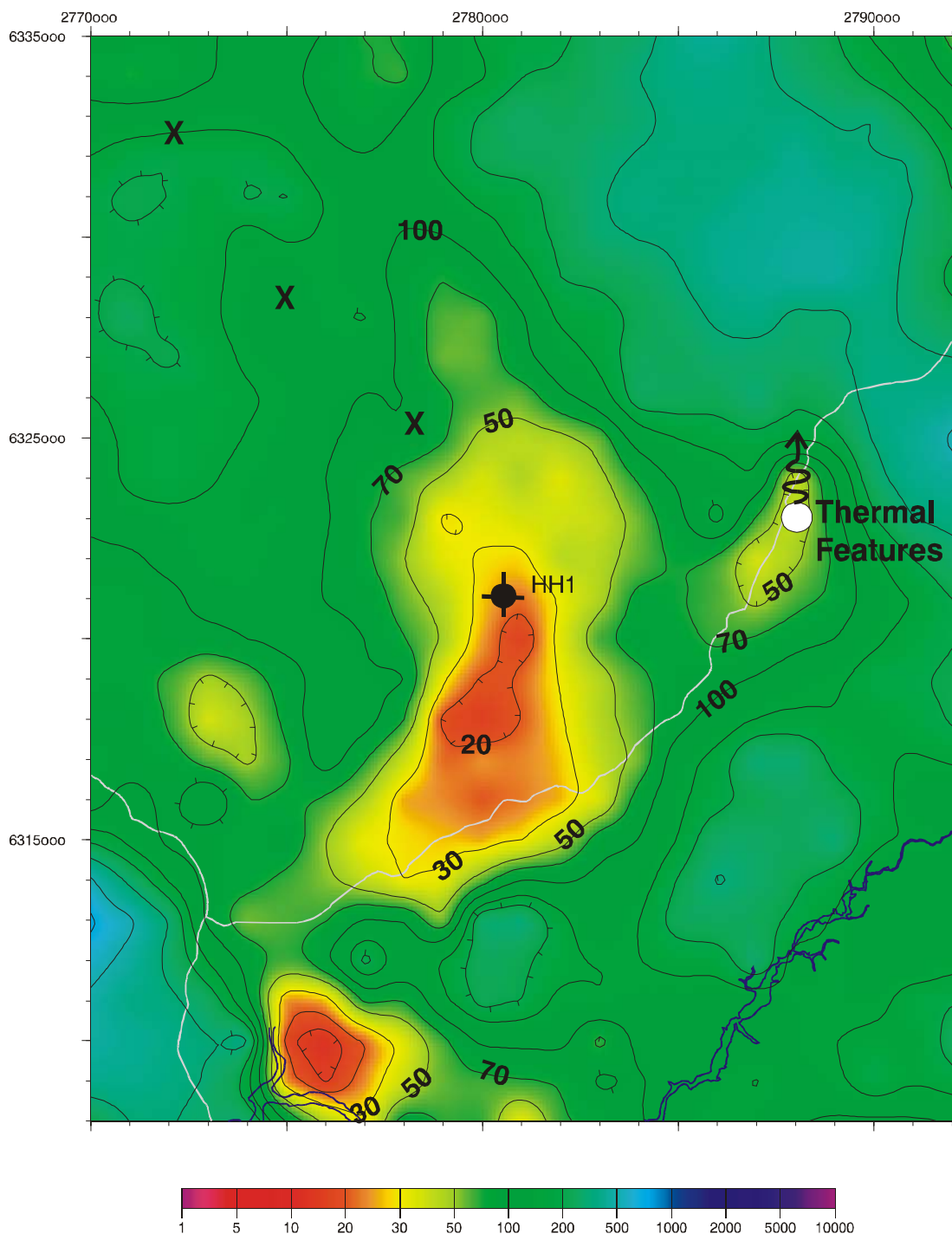


Figure 2: Map of Horohoro – Mamaku region in the north-west of the TVZ showing contours of apparent resistivity measured with Schlumberger electrode array (AB/2 = 1,000 m). Horohoro thermal springs and drillhole HH1 are marked. Crosses mark the sites of the resistivity soundings (Fig.3).

3. HOROHORO DRILLHOLE

The Horohoro thermal area comprises a small region of hot ground and thermal features located about 2 km east of the Horohoro Cliffs within the Guthrie graben (Fig. 2). The discharging thermal waters are dilute (150 - 170 mg/kg Cl; Allis *et al.*, 1987), with a maximum temperature of about 80°C. Chemical and gas isotope data indicated dilution is occurring, consistent with the thermal fluids having travelled some distance from a high-temperature source. Resistivity mapping in the region revealed only a relatively small low-resistivity zone in the vicinity of the hot springs. This anomaly was detected by mapping using Schlumberger arrays with spacings (AB/2) of both 500 m and 1000 m. The apparent resistivity increases with depth near the springs, which was interpreted at that time as indicating cooler, more dilute water at depth (Allis *et al.*, 1987). In retrospect, the observed increase of resistivity with depth is a characteristic of most geothermal systems within the TVZ and is caused by change in the alteration mineralisation from low-temperature, conductive (illite-smectite) to high-temperature, resistive (chlorite) species (Björnsson *et al.* 1986). Indeed, this characteristic increase in resistivity is widely recognised in high temperature geothermal systems (Anderson *et al.* 1999).

Another more extensive low-resistivity zone was also detected by the resistivity mapping. This zone lies within the Matahāna basin about 7 km west of the Horohoro geothermal features (see Fig. 2). Although only a small area of low resistivity was detected in this area using the Schlumberger array with (nominal) AB/2 of 500 m (Fig. 1), mapping using the deeper penetration array (AB/2 of 1,000 m, Fig. 2) indicated a larger zone with resistivity less than 20 Ωm. Interpretation of the resistivity pattern was keenly debated at the time. One postulate suggested that the low-resistivity zone in the Matahāna basin represented a deep geothermal system from which thermal waters flowed laterally to reach the surface at Horohoro springs to the east. Based on this suggestion, it was decided to site an exploratory drillhole (HH1) within the Matahāna basin near the northern limit of the low-resistivity zone (Fig. 1) in order to investigate the geothermal potential of the region. The hole was completed to 593 m depth in March 1986. Temperatures reached a maximum of about 80 °C at hole-bottom, with a nearly linear gradient of about 130 °C/km. No geothermal fluids were found in the hole. It is clear that the cause of the low resistivity was not geothermal fluids. However, the implication of this non-geothermal resistivity anomaly is an important factor that must be taken into account in the interpretation of resistivity data throughout the TVZ.

4. LOW RESISTIVITIES WEST OF THE TVZ

There is considerable evidence to show that the Matahāna basin low-resistivity anomaly is part of a widespread, regional, low-resistivity structure. The regional resistivity investigations included many Schlumberger resistivity soundings. All the soundings made to the west of the Horohoro springs (the Mamaku plateau) including those in the vicinity of HH1 show the presence of a low-resistivity layer ($\leq 20 \Omega\text{m}$) with an upper surface at depths between 200 and 500 m (Fig. 3). In particular, there is little difference that distinguishes the resistivity sounding in the vicinity of HH1 from a sounding made 18 km to the west of the drillhole. The consistency of the soundings suggests that the low resistivity observed in the Matahāna basin is not a localised conductive feature. The anomaly in the vicinity of the drillhole appears to be caused by the regional

low-resistivity layer being fractionally shallower in this vicinity.

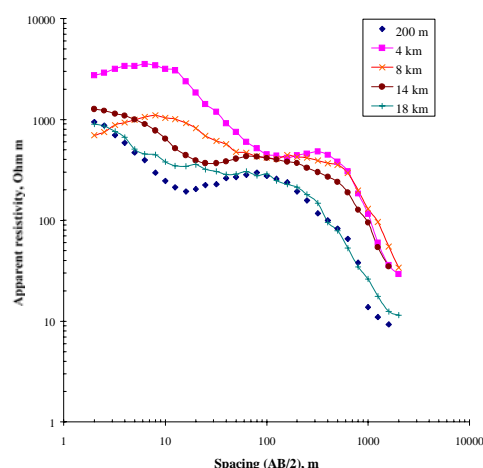


Figure 3: A selection of Schlumberger resistivity soundings measured on the Mamaku plateau. Sites are chosen at a range of distances from HH1 as indicated. Sites of those soundings closest to HH1 are shown in Fig. 2 (two sites lie west of the figure).

This suggests a local thinning of the resistive surface layer that overlies the widespread low-resistivity layer.

Further evidence of the regional extent of the low-resistivity layer can be obtained from an inspection of the GNS resistivity database (Bibby 1988) which incorporates data from a very much wider area. The ratio of the apparent resistivities measured using the Schlumberger array with AB/2 of 500 m and 1000 m can be used to indicate conductive structure at depth. For the sounding curves measured over the conducting layer (shown in Fig. 3) the ratios $\rho(\text{AB}/2=500)/\rho(\text{AB}/2=1000)$ are all greater than 3. The ratios determined from the resistivity mapping program are similar (>3) for almost all the measurements made on the Mamaku plateau covering an area that extends to the west and north of the drillhole. Indeed this low-resistivity layer can be traced continuously in a band of at least 20 km wide along the west side of the TVZ and can be traced to the north side of Lake Rotorua as far as Kawerau. This decrease in resistivity with depth is in marked contrast with the data from within known geothermal systems where the resistivity at similar depths increases with depth.

4.1 The conductive material

Ignimbrites dominate the stratigraphy of HH1; six separate ignimbrite sheets have been identified (Allis *et al.*, 1987). Grindley *et al.*, (1988), fission-track dating techniques were used to estimate the ages of the lowest two sheets at $2.06 \pm 0.13 \text{ Ma}$ and $1.84 \pm 0.18 \text{ Ma}$. This was done by assuming that the stratigraphic units given by Lloyd (in Allis *et al.*, 1987) correspond with those of Grindley *et al.* (1988). The ages of the ignimbrites are plotted against depth in Fig. 4. Also shown are resistivity values from core measurements and down-hole logs. Both indicate very conductive strata in the bottom part of the hole below about 350 m. The resistivity of the core taken from the deepest ignimbrite penetrated (below 470 m) is less than $10 \Omega\text{m}$. Overlying this layer is a thick sequence of ignimbrites with measured (core) resistivities of about $30 \Omega\text{m}$.

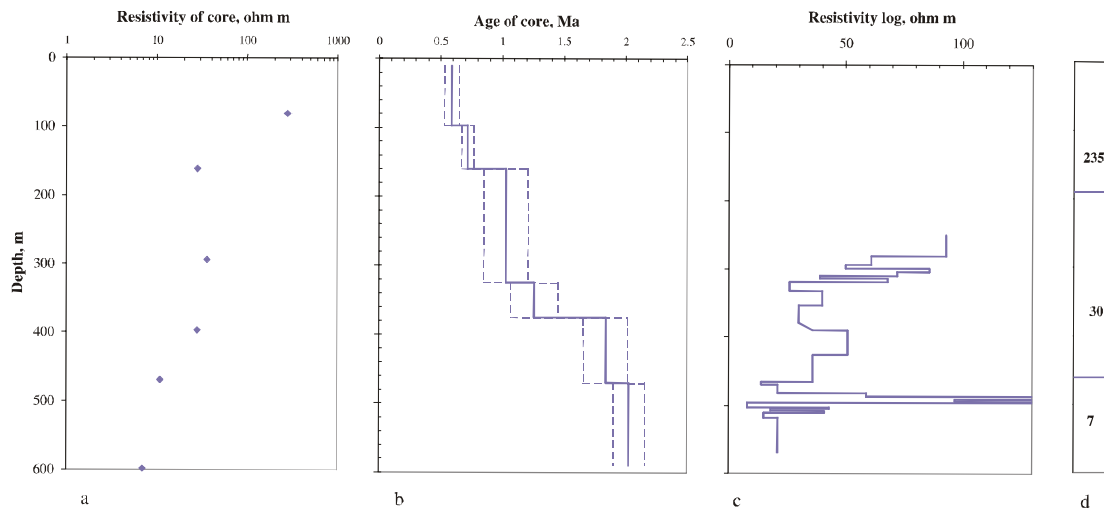


Figure 4: Data from hole HH1. (a) resistivities of cores (in Ωm); (b) age of cores; (c) resistivity from down-hole logging; (d) resistivity derived from the Schlumberger resistivity sounding 200 m from HH1

An estimate of the depths to the main conductive units can also be inferred using resistivity sounding centred about 200 m west of HH1. The sounding data were inverted with the resistivities of the two deepest layers constrained to those measured on the cores (30 and 7 Ωm). The interpreted resistivity section (Fig. 4) gives the depths to the upper surfaces of the two conductive units as 189 m and 461 m, in reasonable agreement with the observed stratigraphic changes at 160 m and 470 m, respectively. Thus the low-resistivity layers observed in the vicinity of the well can be identified as a sequence of older (> 1 Ma) ignimbrites all of which are conductive. The lateral continuity of these low-resistivity layers shown by the Schlumberger array measurements suggests that these old ignimbrites form a continuous sheet over a very wide area west of the Horohoro fault, and in most places are buried under a few hundred metres of younger, resistive volcanoclastics. Petrological studies of the ignimbrites encountered below 300 m in HH1 show that they contain low-temperature hydrothermal alteration products (Allis *et al.*, 1987). The presence of the alteration products (clay and zeolite minerals) allows electric conduction along crystalline interfaces of the particles, which results in the characteristic low resistivity values.

The extensive nature of the low-resistivity layer and its clear correlation with old ignimbrites suggests that low resistivity may be characteristic of all old ignimbrites in the TVZ. This is supported by other observations. Fig. 5 shows a compilation of *in situ* resistivity measurements on ignimbrite outcrops of known ages, together with the data from the cores from HH1. The outcrop measurements were made at type-locations and were clear of any hydrothermal phenomena. Fig. 5 shows that ignimbrites younger than 0.5 Ma have resistivities between 300 and 550 Ωm . Two samples for ignimbrites with ages between 0.5 and 1.0 Ma both give similar high resistivities. The major change occurs at about 1 Ma. All the measurements on ignimbrites older than 1 Ma showed resistivities less than 35 Ωm – smaller by an order of magnitude than the resistivities of the younger samples. The cores from HH1 suggest that the low resistivities are caused by low-temperature alteration within the ignimbrites.

Electrical properties of rocks are very sensitive to the presence of the clays and zeolites that are produced by

alteration processes. Early in the low-temperature alteration process in the ignimbrites, clays will be formed in minute amounts as separate unconnected particles, and their presence will have little influence on rock resistivity. As alteration proceeds, there comes a time at which connected low-resistance clay paths are formed. At this time (or rock age) the rock resistivity abruptly drops. As the alteration process continues multiple paths are formed, causing the resistivity to drop even further. The process envisaged can be represented by an analogue model consisting of a network of resistors each of which may randomly be changed from a resistive to a conductive state (Bahr 1997).

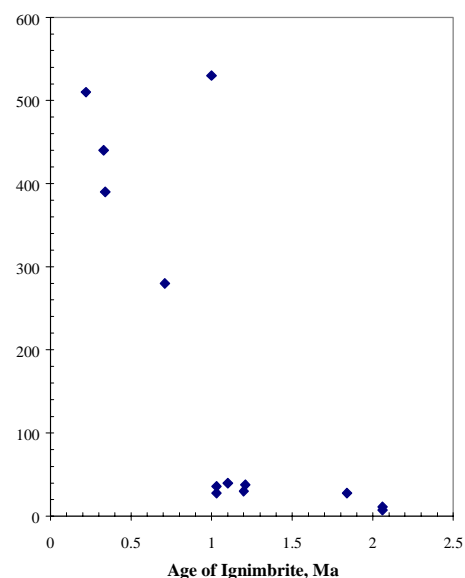


Figure 5: Resistivity with age of ignimbrite rocks from the TVZ. Data from HH1 cores and measurements made *in situ* on rock outcrops.

When a percolation threshold is passed, sufficient conductors are present in the network to form connected paths, and the network moves rapidly from an overall resistor to a conductor. The data from HH1 mimics this process and suggests that, for the ignimbrites of the TVZ, the characteristic time for conductive paths to form is about 1 Ma. The time for the development of these conductive

paths may also be affected by other factors such as the degree of welding (affecting porosity and compaction). Indeed, the exceptionally highly welded Rocky Hill ignimbrite, with an age of about 1 Ma (Wilson *et al.*, 1995), does not fit the pattern of Fig. 4. This unit has an unusually high characteristic resistivity of over 500 Ωm .

The investigation of thermal alteration processes in TVZ ignimbrites by Ellis (1962, 1965) included a study of the variation of the rate of alteration with temperature. The primary interest of this work was to determine the contribution of the heat generated during the devitrification process to the geothermal heat flux. Ellis (1962) extrapolated his laboratory results on devitrification rates and suggested that at near ambient temperatures the alteration process would take about 1 to 2 Ma. The change in electrical resistivity with age, which can also be regarded as a measure of the rate of the alteration process, is in surprisingly good agreement with this estimate.

The devitrification process is exothermic, and the amount of energy generated is considerable ($\sim 3 \times 10^5$ J/kg). Such a heat source in the ignimbrites will increase both the temperature and the temperature gradient within and above these strata. Indeed, this process may contribute to the elevated temperature gradient observed in HH1.

5. CONDUCTIVE NON-GEOTHERMAL ROCKS ELSEWHERE IN TVZ

From the age and geological history of the TVZ, it is clear that ignimbrite layers older than 1 Ma will be present at depths beneath most of TVZ. Thus, even below non-thermal ground, we would expect to find low-resistivity material ($< 20 \Omega\text{m}$) at depths beneath the TVZ. As the products from low temperature alteration (devitrification) are more conductive than those resulting from the high temperature alteration beneath geothermal systems, identification of geothermal systems underground will be difficult.

Deep conductivity zones will have different characteristics depending on whether they lie within or outside the TVZ. Within the TVZ, numerous caldera eruptions from over a period of 2 Ma have resulted to an overlapping and coalescing pattern of caldera collapses and disruptions to the stratigraphy. Outside the TVZ, typified by the region west of Horohoro, the stratigraphy is well preserved. Each (distant) eruption will have added another layer of ash and ignimbrite in an ordered sequence above the resistive basement rocks, so that the older ignimbrites are found within a well defined layered structure with thickness of 1 to 2 km (Ogawa *et al.*, 1999). The extent is clearly shown in the electrical mapping discussed above. Electrical surveying to investigate geothermal fields on the western and northern edges of the TVZ are likely to encounter these conductive structures. Without the knowledge and awareness of these conductive layers it would be easy to confuse the geothermal and non-geothermal signatures. In addition to the Horohoro geothermal area, other geothermal systems that may encounter these layers include Mangakino, Rotomahana and Kawerau.

Within the complex structures of the TVZ stratigraphic relationships are not simple. Conductive material may be expected to exist within deep collapse features – often the locations of geothermal systems. The existence of deep highly conductive basins along both the eastern and western margins of the TVZ has been demonstrated by deep penetrating DC electrical studies (Risk *et al.* 1993, Bibby *et al.* 2002). Fig. 5 shows the inferred resistivity structure across the western and eastern margins of the TVZ. The eastern transect passes between the Ohaaki and Rotokawa geothermal fields. The line was chosen to cross high-resistivity ground, well away from known thermal areas. Similar resistivity cross-sections were obtained along several other E-W profiles across the eastern margin, together spanning a 30 km wide zone. All models of the resistivity structure show resistivities of about 30 Ωm between 0.5 and 2 km depth, and a very conductive zone below 2 km. While the resistivity and thickness of the deep conducting layer cannot be uniquely determined, the

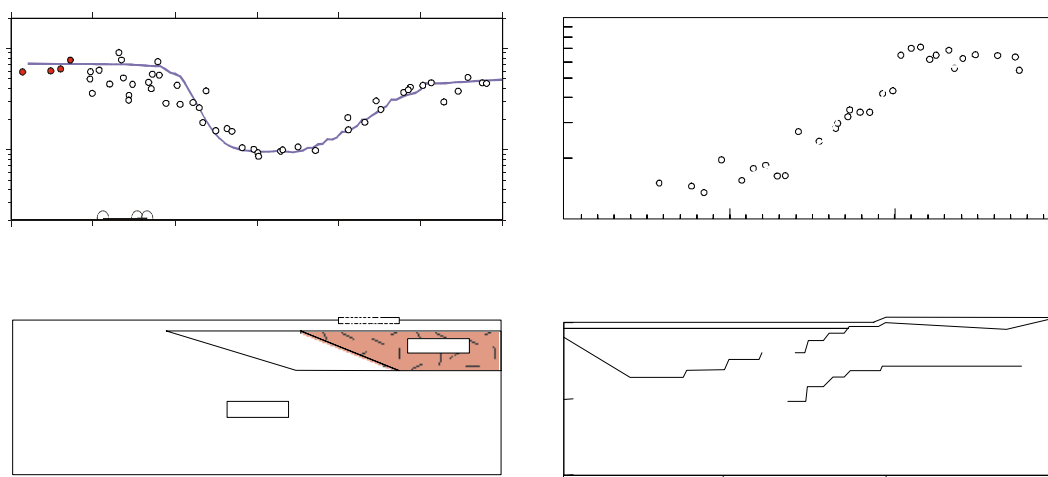


Figure 6: Resistivity structure on the western and eastern edges of the TVZ derived from large scale tensor resistivity surveys. Note the extensive regions of low resistivity at depth necessary to match the measured data.

total conductance (depth/resistivity) is well defined. Our preferred model (Fig. 5b) for the eastern basin has a 2-km-thick layer of 5 Ωm material. The extent of this zone is many times larger than the diameter of the average TVZ geothermal system. The existence of this deep and highly conductive basin has also been observed in magnetotelluric measurements made in the same region (Ogawa *et al.* 1999). Bibby *et al.* (1998) suggest that the conductor represents old clay- and zeolite-rich volcanoclastics that fill the deeper levels of a series of coalescing calderas along the margin.

There is no requirement for this low-resistivity material to be related to geothermal processes, and indeed, such extremely low resistivity is a characteristic of low-temperature alteration. In this environment it will be very difficult to use electrical techniques to distinguish the signature of the deeper parts of the geothermal systems from the conductive background of old volcanics. Furthermore, the low-resistivity material that is expected to exist at depth between geothermal systems could be misinterpreted as a hydrothermal connection between the systems.

6. CONCLUSIONS

In the TVZ, it has often been tacitly assumed in the past that there is a one-to-one relationship between low resistivity and the presence of geothermal water. Although every known geothermal system in the TVZ has an associated low-resistivity signature the converse is not true. Electrical prospecting is highly successful in the TVZ because the upper 500 to 1000 m of material is composed almost entirely of young volcanoclastic rocks that have high resistivities, creating a strong, near-surface contrast in resistivity between geothermal and non-geothermal areas.

With age, the devitrification process within the cold volcanoclastic rocks results in conductive clays and zeolites being formed within the rock matrix. When this process has advanced sufficiently for continuous conductive paths to be formed within the rock the electrical resistivity drops by about an order of magnitude. In the TVZ, ignimbrites older than about 1 Ma are conductive, even though their temperatures may never have been significantly above ambient. The presence of clays within the interstices of these rocks would also be expected to reduce permeability.

In the western part of the TVZ, older conductive ignimbrites, underlain by a resistive basement, are widespread and occur within 400 m of the surface over much of the Mamaku plateau. Using resistivity techniques in these areas to delineate geothermal fields is problematic. For example, at Mangakino the low-resistivity signature of the geothermal field is difficult to distinguish from the background of low resistivity caused by the presence of old ignimbrites.

Large thicknesses (>2 km) of conductive material are also found along the eastern margin of TVZ at depths of about 2 km. This low-resistivity rock is believed to be old volcanoclastic material that has filled a series of overlapping collapsed calderas (Risk *et al.*, 1993; Bibby *et al.*, 1998). Because these low-resistivity zones are extensive at depth along the eastern side of the TVZ, caution is required in the interpretation of electrical measurements. Claims of hydrological connection between adjacent geothermal fields based on apparent connection by deep-seated low-resistivity structures can be erroneous. Such low-resistivity structures may not be associated with geothermal waters at all. The low-temperature alteration process described here may give

an equally valid explanation for the existence of extensive regions of low-resistivity rock.

With the renewed interest in geothermal exploration in New Zealand, it is appropriate to sound a warning based on past experience. This is particularly important as the simple resistivity techniques of the past are supplanted by modern magnetotelluric measurements which are capable of much greater depths of penetration and which will frequently encounter conductors of non-geothermal origin during geothermal investigations. To correctly identify deep geothermal structures requires knowledge of all the factors that may influence the electrical conductivity of the rocks, both geothermal and non-geothermal.

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