THE MATAHANA BASIN RESISTIVITY ANOMALY: IMPLICATIONS FOR GEOTHERMAL EXPLORATION IN THE TAUPO VOLCANIC ZONE

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SUMMARY – In 1986, a 593m hole was drilled into a low-resistivity anomaly, identified by Schlumberger-arraymapping, at Matahana Basin in the north-westem part of the Taupo Volcanic Zone. Unlike comparable exploration holes in other low-resistivity anomalies in the TVZ, this hole was cold. We show that the low-resistivity material can be identified as ignimbrites older than 1Ma. The low resistivity is caused by a process of devitrification within the ignimbrites, leading to the formation of conductive minerals (clays and zeolites) within the rock matrix. At near ambient temperatures this process causes more than an order-of-magnitude reduction in resistivity after ca. 1 Ma. Conductive rocks produced by this process are expected to exist at depth throughout most of TVZ. Misinterpretation of the resulting low-resistivity anomalies as indicating hydrothermal conditions must be avoided.

1. INTRODUCTION

Electrical resistivity prospecting techniques have been very successful for determining the extent of geothermal systems within New Zealand's Taupo Volcanic Zone (TVZ). Maps of electrical resistivity (e.g. Bibby, 1988; Stagpoole and Bibby, 1998) show 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 a conducting electrolyte within a conductive rock matrix; the conductivities of both the electrolyte and the rock matrix are temperature dependent in a manner that causes a large reduction of the bulk resistivity with increasing temperature. A third factor affecting rock resistivity is alteration of the rock matrix caused by prolonged exposure to high-temperature waters. The alteration products (clays and zeolites) greatly reduce the resistivity of the rock matrix (Caldwell *et* al., 1986).

There is another factor that contributes to the success of resistivity techniques in the TVZ. The upper kilometre of the TVZ comprises young (< 330 ka) volcanic rocks which (away from the geothermal fields) have resistivities greater than 100 Ωm. It is the large contrast between the conductive rocks within the geothermal systems and the surrounding rocks that allows the extent 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). Indeed, the Schlumberger-array resistivity mapping techniques were designed to penetrate to depths of only a few hundred metres where the resistivity contrast is at its maximum.

The overwhelming success of resistivity mapping for geothermal prospecting has led to a lack of care in the interpretation of resistivity data. In particular, it is very easy to assume that low-resistivity anomalies, whatever their depths or locations, indicate the presence of geothermal waters. The purpose of this paper is to review the data from the Horohoro drill hole (HH1), where this assumption was proved incorrect. We show that low resistivities in the TVZ are also associated with old (>1 Ma) ignimbrites which occur at shallow depths on the west side of the TVZ and at greater depth elsewhere.

2. 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. 1). Resistivity mapping in the region revealed only a relatively small low-resistivity zone in the vicinity of the hot springs. The anomaly was detected using Schlumberger arrays with spacings of both 500m and 1000m although the resistivity appeared to increase with depth in this area, which was interpreted as indicating cooler, more dilute water at depth (Allis *et al.*, 1987).

The 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, consistent with the thermal fluids having travelled a considerable distance fiom a high-temperature source.

Another more extensive low-resistivity zone was also detected by the resistivity mapping. This zone lies within the Matahana basin about 7 km west of the Horohoro springs (see Fig. 1).

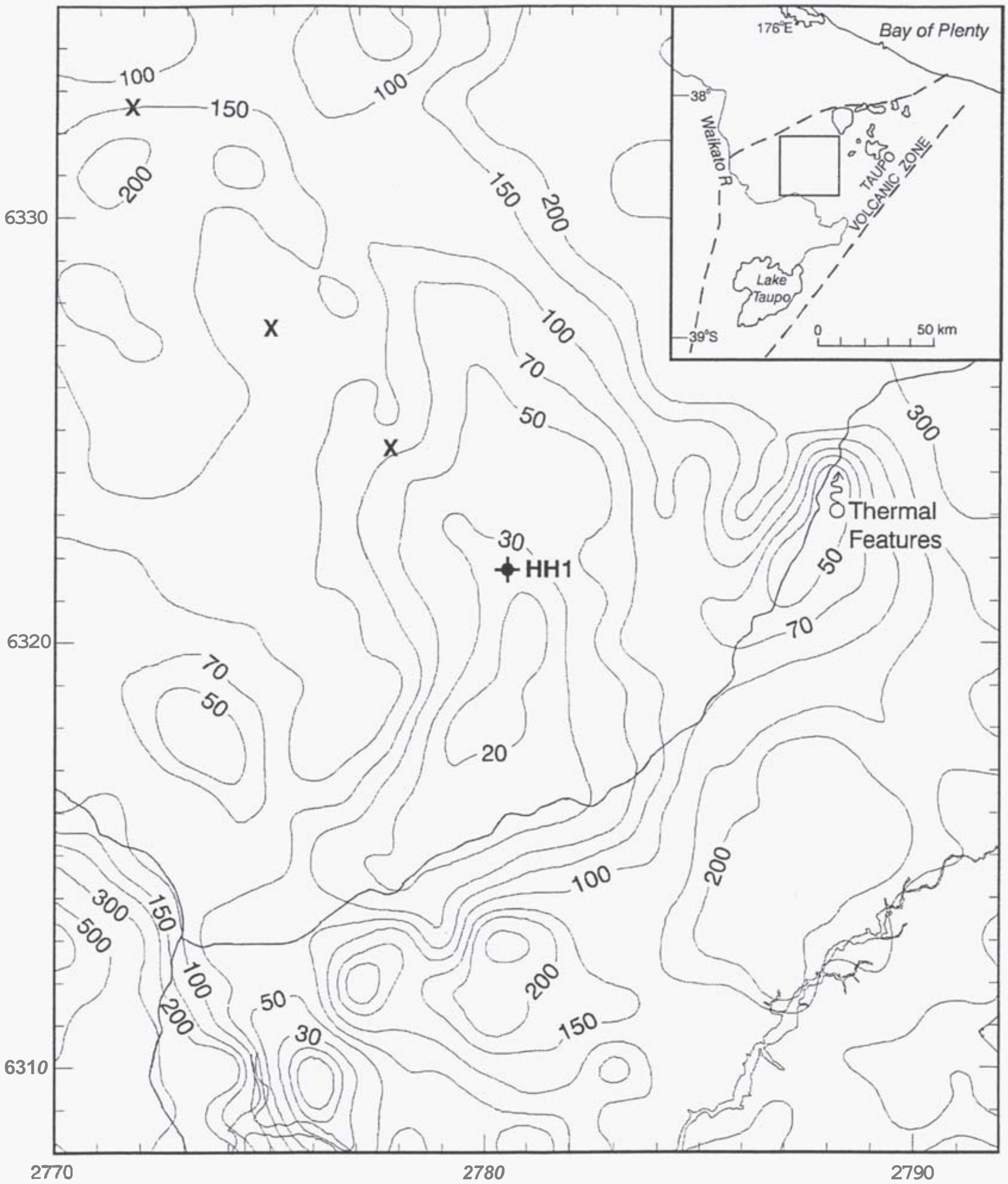

Figure 1: Map of Horohoro – Mamaku region in the north-west of the TVZ showing contours of apparent resistivity measured with Schlumberger electrode array (AB/2 = 1,000 m). Horohoro thermal springs and drillhole HH1 are marked. Crosses mark the sites of the resistivity soundings (Fig.2).

Although only a small area of low resistivity was detected using the Schlumberger array with a spacing of 500 m, the 1,000 m array mapping indicated a large 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 Matahana basin represented a deep geothermal system from which thermal waters were transported laterally to reach the surface at Horohoro springs to the east.

Based on this suggestion it was decided to site an exploratory drill-hole (HH1) within the Matahana 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. However, we can now identify the cause of the low-resistivity zone, and assess its implications.

3. LOW RESISTIVITIES BENEATH THE MAMAKU PLATEAU

There is considerable evidence to show that the Matahana basin low-resistivity anomaly is part of a widespread, regional, low-resistivity structure. The regional resistivity investigations included extensive resistivity soundings. All the soundings made on the Mamaku plateau and those in the vicinity of HH1 show the presence of a low-resistivity layer (< 20 Ωm) at depths between 200 and 500 m (Fig. 2). The consistency of the soundings suggests that the resistivity low observed in the Matahana basin is not a localised conductive feature. Instead it reflects a localised thinning of the resistive surface layer that overlies the widespread low-resistivity layer.

Further evidence of the regional nature of the low-resistivity layer can be obtained from the GNS resistivity database (Bibby 1988). The ratio of the apparent resistivities measured using the Schlumberger array with spacings of 500 m and 1000 m can be used to indicate conductive structure at depth. The sounding curves measured over the conducting layer (shown in Fig. 2) have ratios (ρ_{500} / ρ_{1000}) greater than 3. The ratios determined from the resistivity mapping programme are similar (>3) for almost all the measurements made on the Mamaku plateau. Thus both resistivity data sets indicate that the low-resistivity layer is continuous and underlies a very large area to the west of the TVZ.

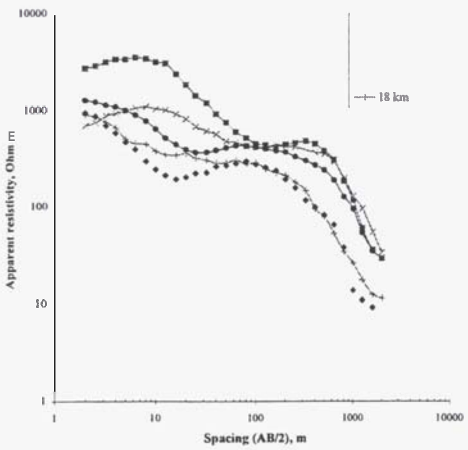

Figure 2: A selection of Schlumberger resistivity soundings measured on the Mamaku plateau. Sites are chosen at a range of distances from HH1 as indicated. Sites are shown in Fig. 1 (two sites lie west of the figure).

3.1 The conductive material

Ignimbrites dominate the stratigraphy of HH1; six separate ignimbrite sheets have been identified (Allis *et* al., 1987). Grindley *et* al., (1988), using fission-track dating techniques, give the ages of the lowest two sheets at 2.06 ± 0.13 Ma and 1.84 ± 0.18 Ma. 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. 3. Also shown are resistivity values from core measurements and down-hole logs, both of which indicate very conductive strata in the bottom part of the hole. The resistivity of the deepest layer penetrated (below 470 m) is less than 10 Ωm. Overlying this layer is a thick sequence of ignimbrites with measured (core) resistivities of about 30 **Ωm**.

An apparent inconsistency occurs between the downhole resistivity log and core measurements at about 260 - 320 m depth. The resistivities of cores from shallower levels suggest little variation in resistivity occurs across this zone. However, the log shows an increase in resistivity (upwards) at about 320 m depth (Fig. 3), near to where a stratigraphic boundary is observed. The apparent increase in the logged resistivity is believed to be caused by the proximity of the logging tool to the bottom of the well casing (known in logging as the Delaware effect).

An estimate of the depths to the main conductive units can also be inferred using the 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 inversion gives the depths to the upper surfaces of the two conductive units as 189 m and 461 m, in good agreement with the observed stratigraphic changes at 160 m and 470 m, respectively. Thus these two low-resistivity layers observed near the well can be identified with 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 volcaniclastics.

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 identification with old ignimbrites suggests that low resistivity may be characteristic of all old ignimbrites in the TVZ. This is supported by other observations. Fig. 4 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 clear of any hydrothermal phenomena. Fig. 4 shows that ignimbrites younger than ***0.5*** Ma have resistivities typically between 300 and **550** Ωm. The two measurements available between 0.5 and 1.0 Ma give similar high resistivities, although the variation is quite large, with the 1 Ma. Rocky Hill ignimbrite having a characteristic resistivity of over 500 Ωm. A major change occurs at about 1 Ma. All the measurements on ignimbrites older than 1 Ma showed resistivities less than 35 **Ωm** – an order of magnitude change from 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, clay will be formed in minute amounts as separate unconnected particles, and

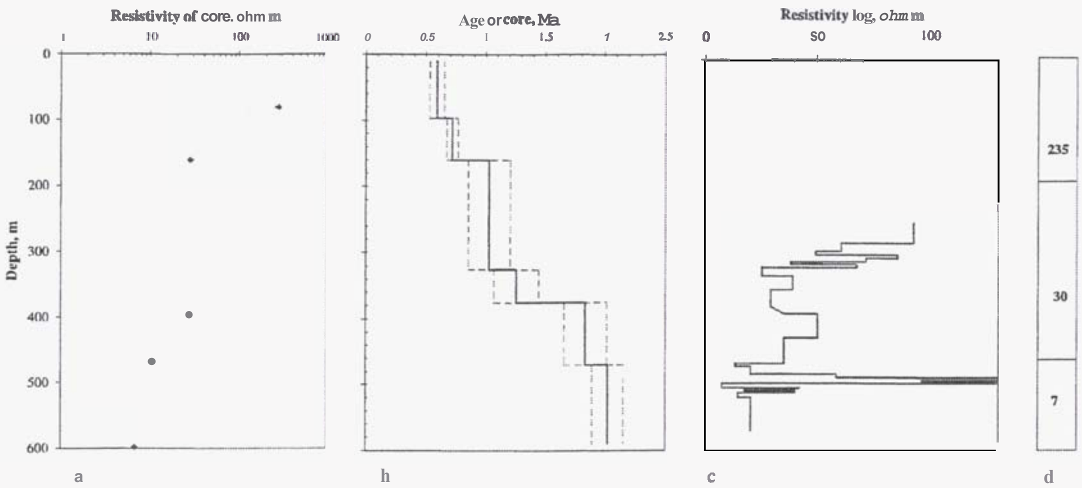

Figure 3: Data from hole HH1. (a) resistivities of cores; (b) age of cores; (c) resistivity from down-hole logging; (d) resistivity (in Ωm) derived from Schlumberger resistivity sounding 200 m from HH1.

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 data from hole HH1 illustrate this process and show that, for the ignimbrites of the TVZ, the characteristic time for conductive paths to form appears to be 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) which may explain the unusually high resistivity found in the highly welded Rocky Hill ignimbrites (Wilson *et al.*, 1995).

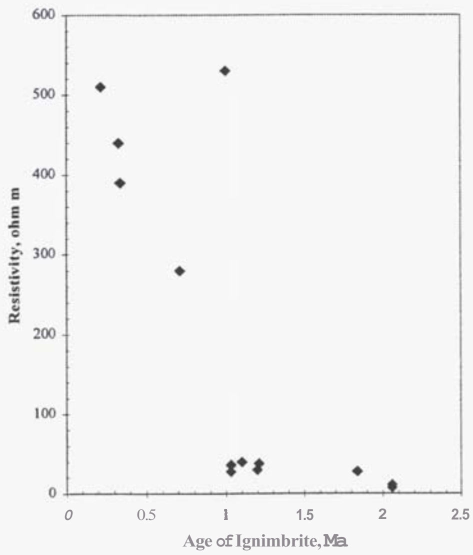

Figure **4:** Resistivity with age of ignimbrite rocks from the TVZ. Data from HH1 cores and measurements made ***in situ*** on rock outcrops.

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 should 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 (~3×10^5 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.

4. CONDUCTIVE NON-GEOTHERMAL ROCKS ELSEWHERE IN TVZ

The age and geological history of the TVZ is such that ignimbrite layers older than 1 Ma. may be present at depth beneath most of TVZ. Thus, even in non-thermal ground we would expect to find low-resistivity material (< 20 Ωm) at depth beneath the TVZ. We have shown here that extensive low-resistivity material occurs on the west side of the TVZ. There is now clear evidence that extensive (non-hydrothermal) conductive material exists elsewhere in the TVZ.

The existence of a deep highly conductive layer along both the eastern and western margins of the TVZ has been demonstrated by deep penetrating electrical studies (Risk *et* al., 1993; Bibby *et al.*, 1998). Fig. **5** shows the inferred

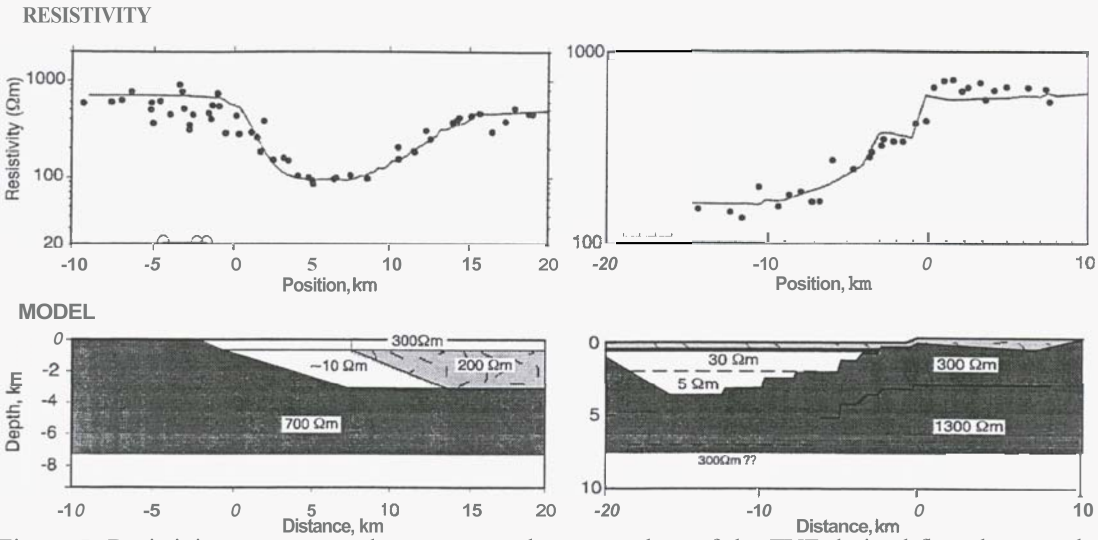

Figure *5:* Resistivity structure on the western and eastern edges of the TVZ derived fkom large scale tensor resistivity surveys. Note the extensive regions of low resistivity at depth necessary to match the measured data.

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 on 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 total conductance (depth/resistivity) is well defined. Our preferred model (Fig. *5)* 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. Bibby *et* al. **(1998)** suggest that the conductor represents old clay- and zeolite-rich volcaniclastics 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 at high temperature, 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 against this conductive background. Further, the low-resistivity material that is expected to exist at depth between adjacent geothermal systems could be very easily misinterpreted as a hydrothermal connection between the systems.

5. CONCLUSIONS

In the TVZ, it has been tacitly assumed 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 volcaniclastic rocks that have high resistivities.

With age, the devitrification process within the volcaniclastic 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, volcaniclastic rocks older than about 1 Ma appear to be 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 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 problematical. 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 volcaniclastic material that has filled a series of overlapping collapse 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 high-temperature 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.

The data obtained from HH1 eliminates the Matahana basin as the source of the thermal waters found at the Horohoro springs. It is possible that the low-resistivity anomaly associated with the Horohoro thermal area may not represent an outflow as has previously been assumed. The nature of this system is poorly understood.

6. ACKNOWLEDGEMENTS

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