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RECENT RESISTIVITY MEASUREMENTS AT TOKAANU-WAIHI GEOTHERMAL FIELD

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SUMMARY – New electrical resistivity measurements have been made in and around the Tokaanu-Waihi geothermal field to augment the existing data set. Measurements were made using several methods including traversing with Schlumberger electrode arrays where vehicle access is possible, equatorial dipole-dipole arrays operated from boats in the south of Lake Taupo and 50Hz magnetotelluric method on the slopes of Kakaramea and Tihia. The resistivity anomaly marking the field extends beneath the waters of Lake Taupo for about 1 km north into Waihi Bay. On the high elevation ground to the west of Tokaanu the boundary is not sharply defined, although it appears to be high up the flanks of Tihia and there is a possibility that westward drainage of geothermal fluids may be the cause of low resistivity to the west of Tihia.

1. INTRODUCTION

The Tokaanu-Waihi geothermal field lies at the southern end of Lake Taupo in the Taupo Volcanic Zone (TVZ) of New Zealand. This is one of only a few geothermal systems in the TVZ that have not been fully investigated using the traditional Schlumberger resistivity traversing technique. The steep terrain of the Kakaramea andesitic cone to the southwest of Tokaanu makes vehicle access impossible, while to the northeast, the waters of Lake Taupo cover a portion of the geothermal system. As a consequence it has been necessary to apply alternative methods to attempt to delineate the geothermal field. This paper presents new resistivity measurements made at the Tokaanu-Waihi geothermal field from 1996 to 1998 that fill in the data gaps. The measurements were made using Schlumberger arrays where vehicle access was available, 50 Hz MT method where only foot access was possible and, on Lake Taupo, waterborne arrays towed behind boats.

2. PREVIOUS RESISTIVITY DATA

The first resistivity measurements in the Tokaanu-Waihi area were made in 1966 using the Wenner array with electrode spacing of 1800 ft (≈550 m). Measurements were made along the main highways only. Later, additional measurements were made using the Schlumberger array with spacings (AB/2) of 500 m and 1,000 m, repeating measurements at some of the sites previously used for the Wenner survey and extending coverage using the better access then available. Complementing the dc resistivity data, magnetotelluric (MT) methods were tested by Reeves and Ingham (1991) over the flat lying eastern boundary of the field. In addition to these data, shallow penetration dc measurements have also been made to investigate local structure near the thermal features. Macdonald (1967) reports a detailed survey in the environs of the Tokaanu power house and tailrace canal using Wenner arrays with electrode spacings of 30 m and 60 m. A shallow-penetration resistivity survey (Schlumberger arrays, AB/2, 50 m and 100 m) of the Hipaua and Waihi part of the field was made by Munyithya (1994). Rwegoshora (1995) made a similar survey along 3 km of the Tokaanu-Rotoaira highway. Data coverage in other areas has been limited by difficult access.

3. RECENT SCHLUMBERGER ARRAY MEASUREMENTS

Between 1996 and 1998 additional resistivity measurements were made along roads and tracks using the Schlumberger array with electrode spacings (AB/2) of 500 m and 1,000 m. This work employed the standard traversing technique that has been used to survey other parts of the TVZ (Bibby 1988). Data were gathered from most of the accessible region to the north of the geothermal field, but vehicle-based measurements were not possible over the steep bush-clad terrain in the southern parts of the field. The extent of the Schlumberger and Wenner resistivity coverage is shown in Fig. 1. Major gaps in the data coverage can be seen in two areas - the high elevation ground of the andesite domes of Tihia and Kakaramea and Lake Taupo in the vicinity of Waihi Bay. In order

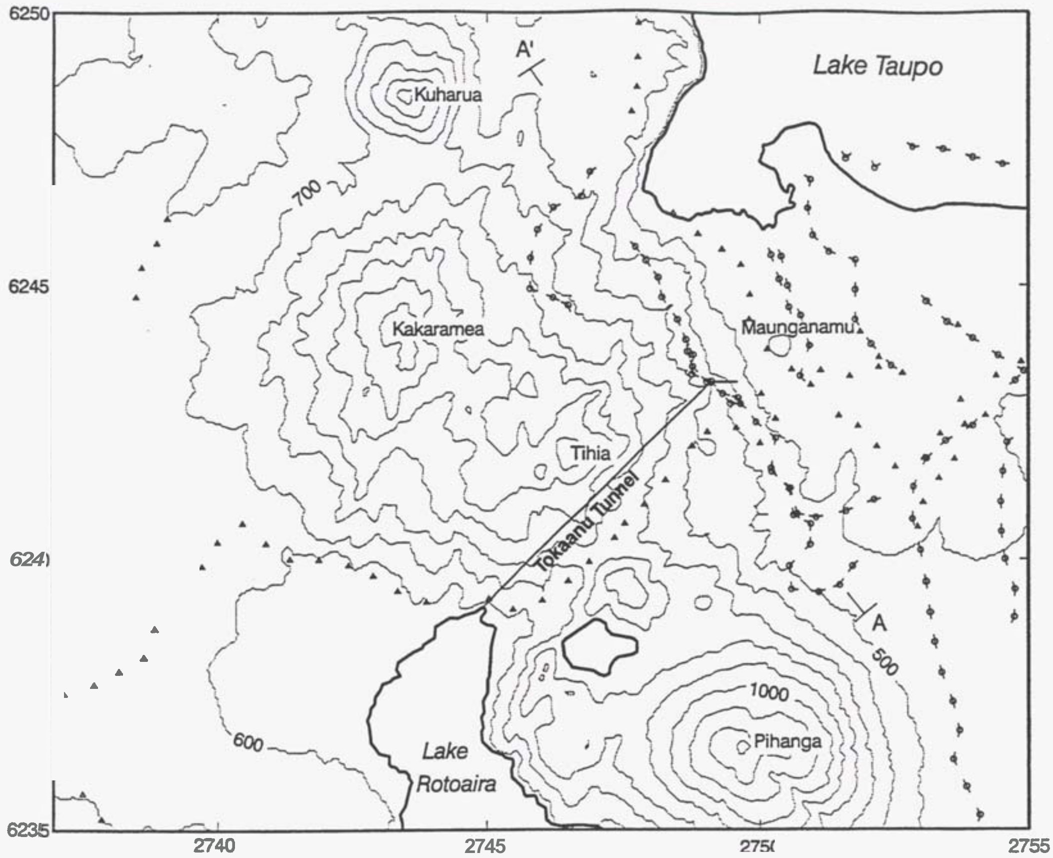

Fig 1: The extent of measurements made with Schlumberger array (AB/2 = 500 m, circles) and the eqivalent Wenner array (triangles)).Background shows contours of topography at 100 m intervals. AA' marks the position of profile shown in Fig, 5.

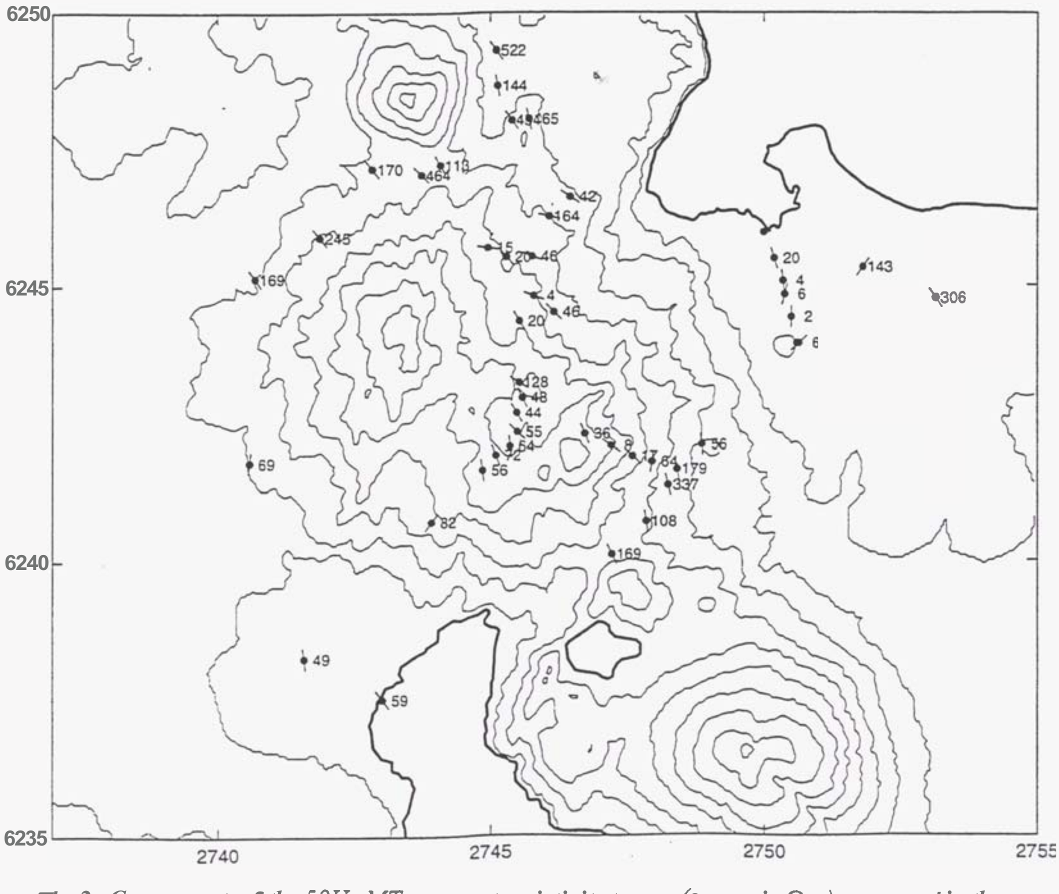

Fig 2: Components of the 50Hz MT apparent resistivity tensor (ρ_{Emax}, in Ωm) measured in the direction of maximum E field which is shown by the bars.

to improve the coverage, non-traditional techniques have been used.

4. 50 Hz MT MEASUREMENTS

The **50Hz** MT method is a variation of the magnetotelluric method of measuring ground resistivity in which the electric and magnetic fields that radiate from 50 Hz power lines are detected at the measurement site using small dipoles and induction coils, as described by Risk et al. (1997). The equipment used is portable and can be carried by two people. Thus, measurements can be made in places that are accessible only by foot. Furthermore the 50Hz signal is measurable throughout the TVZ

Methods for determining the apparent resistivity tensor and various scalar apparent resistivities from the measured data are discussed by Risk et al. (1997). At many of the sites the 50 Hz electric fields (E) are strongly polarised in a dominant direction, with the result that some components of the apparent resistivity tensor can be better determined than others. At all sites the component of the apparent resistivity tensor ρ_{Emax} in the direction of the dominant polarisation of the electric field is well determined. For consistency we thus use ρ_{Emax} in this paper because it provides a uniform data set. Furthermore, in this environment, the data obtained are comparable to the Schlumberger (AB/2 = 500 m) resistivities. Values of ρ_{Emax} are shown in Fig. 2. Short bars at the measurement sites indicate the direction of maximum **E** polarisation. The direction of E_{max} is influenced by both the electrical structure and the distribution of the sources of the 50Hz signal. For the majority of these sites the local resistivity structure dominates.

5. LAKE RESISTIVITY MEASUREMENTS

Caldwell and Bibby (1992) describe a waterborne resistivity survey of Lake Taupo, including details of the measurement method. Measurements are made using two boats moving abreast along parallel tracks, 500 m apart. Each boat tows an electrode array, which comprise a 150 m long electrode dipole. One dipole injects current into the water and the other measures the resultant voltages. Together, the electrodes form an equatorial dipole-dipole array which, in a horizontally layered earth, is equivalent to a Schlumberger array with spacing AB/2=500 m. This method allows data to be gathered rapidly in water covered areas and, unlike the techniques previously used (Bennie et al., 1983), it is not limited by water depth.

The direction of current in the current dipole was reversed every 4 seconds corresponding to a measurement about every 10 m. A continuous log of voltage in the receiver dipole was recorded on a laptop computer. GPS recorders on both boats logged the tracks of the boats. Data analysis used the method described by Caldwell and Bibby (1992). The first step was to determine from the navigational data the positions of the four electrodes at the instant of each switch. From this the geometric factor was determined and then the apparent resistivity calculated. The variation in apparent resistivity is shown in Fig. 3.

In the earlier survey of Caldwell and Bibby (1992) the most southerly data on Lake Taupo were measured on an east-west line 4 km north of the southern shore and did not detect the Tokaanu-Waihi low-resistivity region. The present work (measured in March 1998) comprises three lines of data that extend the survey closer to the shore in Waihi Bay (Fig. 3). Two of the lines track north-south into Waihi Bay while the third runs east-west just off the Tongariro river mouth.

Data with good-signal to-noise ratio was measured in the lake away from the shore, but problems were encountered near the shore in Tokaanu Bay where the wires snagged on weeds in the shallow water creating unwanted electrical noise. Thus, on the eastern line, reliable measurements were not obtained as far into Waihi Bay as was intended.

6. DISCUSSION

Fig. 4 is a combined plot of the apparent resistivity data measured using the Schlumberger array with spacing AB/2=500 m and all the other measurements that have a similar penetration depth. Each of these data sets (Wenner, Schlumberger, 50 Hz and waterborne) give apparent resistivity values which are an approximate average of the resistivity in the upper few hundred metres of ground. The shaded grey scale on Fig. 4 indicates the resistivity values; darker shades indicating lower resistivity. Contours for 20 and 100 Ωm are shown. The resistivities of less than 20 Ωm measured over the central parts of the Tokaanu-Waihi field (Fig. 4) indicate the presence of geothermal waters. Values greater than 100 Ωm suggest cold conditions.

In the east, the resistivity boundary of the field to a few hundred metres depth is reasonably well defined by the data and lies close to the Tokaanu tailrace canal, in agreement with shallow surveys of Macdonald (1967). The MT measurements made by Reeves and Ingham (1991) near the canal show a rapid change in the shallow resistivity at a position that is in good agreement with the boundary seen by our measurements. At greater depths, the deeper penetration MT resistivity shows low resistivity further to the east, suggesting the boundary may slope away

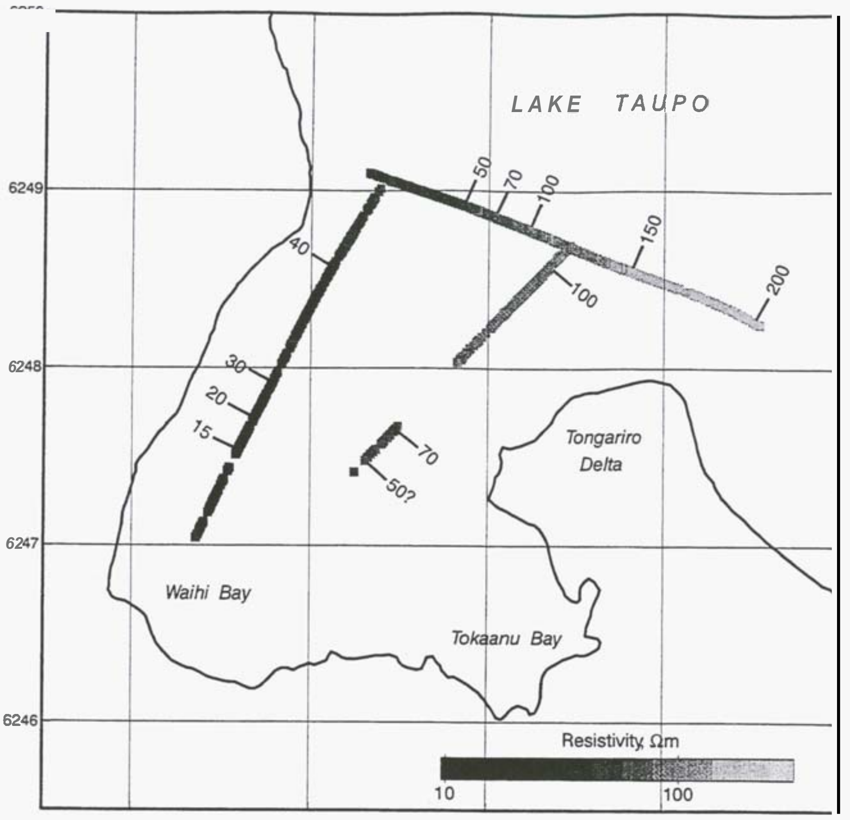

Fig. 3: Survey of apparent resistivity in Lake Taupo. Values of apparent resistivity are shown by a grey scale with low resistivity shown in darker shades. Measurementpoints at the are the mid-points of the tracks of the boats. Specific contours of apparent resistivity (in Ωm) are also shown.

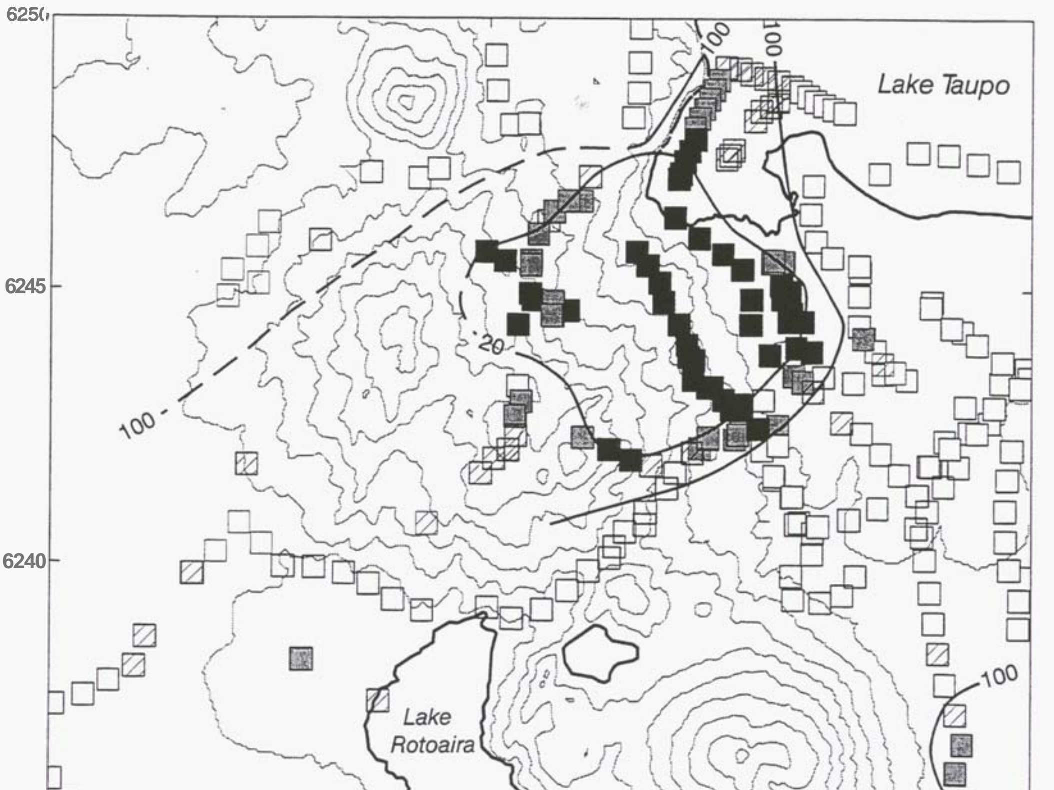

Fig. 4: Combined plot of the apparent resistivities (in Ωm) measured with the Wenner, Schlumberger (AB12 = 500 m), 50Hz MT and waterborne methods, Resistivity values are shown in four bands: Black <20 Ωm, grey 20-50 Ωm, hatched 50-100 Ωm, clear > 100 Ωm.

from the geothermal system, as has been observed in other geothermal fields in the TVZ (e.g. Bibby, **1978).**

Within Lake Taupo (Fig.3) a low resistivity zone (< 15 Ωm) extends under the lake for over **1 km** north in Waihi Bay. This zone lies offshore from thermal ground at Waihi village, which has been mapped using infra-red techniques by Bromley and Mongillo **(1991).** Thus, thermal fluids underlie the southwest comer of the bay although this may be an outflow from the geothermal system further to the south. Further north, within the lake, a band of intermediate resistivities **(40 – 50 Ωm)** occurs along the western side of the lake (Fig. 3). We suggest this represents clay rich sediments derived from the west and south (possibly hydrothermally altered landslide material). In contrast, the higher resistivities **(70 – 200 Ωm)** that are found further east near the Tongariro delta (Fig. **4)** indicate a lack of thermal activity and reflect the fresh clean sands recently deposited by the Tongariro River.

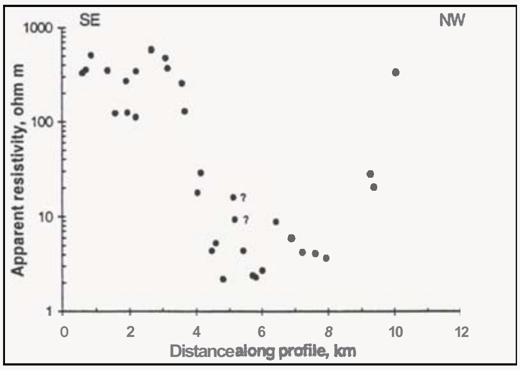

Fig. 5: Apparent resistivity along profile AA′ (Fig.1) showing the abrupt change that occurs at the boundary of the geothermal system. Data points for which the potential array lies over the Tokaanu Tunnel are shown with question marks.

The boundaries to both the northwest and southeast of the Tokaanu geothermal field are narrow zones, typical of the boundaries found at other geothermal fields in the TVZ. The contrast in resistivity can be seen in the profile of the resistivity data along line AA′ shown in Fig. **5.** Resistivity values of several hundred Ωm are found to both the southeast and northwest, and contrast strongly with the low resistivities observed within the geothermal field. Although the southeastern boundary is very sharply defined along this profile, a gap in the data occurs near the boundary to the northwest, where access was restricted. In Fig. **5,** the two highest values of resistivity measured within the geothermal field were observed using potential electrodes almost directly above the tunnel that carries water to the Tokaanu power station (see Fig. **1).** These measurements are regarded as suspect.

The most difficult part of the boundary to investigate is that to the southwest on the flanks of Kakaramea and Tihia. Not only is the access difficult, the terrain on the andesite cone influences the hydrology. On the flanks of Kakaramea, the ground water table becomes systematically deeper at higher elevation. Thus the geothermal waters will be at greater depths on the southwestern boundary of the field and will not be as easy to detect as at lower elevations. The nature of the geothermal features also reflects this effect, with high elevation features being predominantly steam heated where as springs dominate at lower elevation. At high elevation, the resistivity of the material above the water table will be affected by the presence of steam, which will cause alteration. Thus, even if the water table is deep, the presence of deep geothermal waters can be distinguished because of the overlying alteration, although the resistivity contrast will be reduced.

On the higher elevation ground near Kakaramea and Tihia, the 50 Hz MT measurement system has been used although the density of measurements is not ideal (Fig. 2). **A** contrast can be seen between the intermediate and low resistivity values measured on the flanks of Kakaramea and the very high resistivities **(>100 Ωm)** measured west of Kakaramea (near Kuharua) and southeast of Tihia (Fig. 2), which clearly lie outside the geothermal field. Thus a good contrast is found between the geothermal and non-geothermal ground in these locations.

In the southwest, a line of 50 Hz measurements on the eastern slope of Tihia crosses the boundary. Resistivities along this line change from more than **100** Ωm to less than 20 Ωm at two sites northeast of the summit of Tihia (Fig. **2).** The hydro tunnel from Lake Rotoaira to Tokaanu (Fig. 1) passes beneath this line. The northern part of the tunnel (ca. **1800** m) contains zones of altered andesites containing a high fraction of montmorillonite and other low-resistivity clays and slightly elevated temperatures **(43°C)** (Hancox, **1974).** Upwelling thermal fluids are thought to have caused the alteration. Thus our data is consistent with the presence of clays. This suggests that the low resistivities at the sites near the summit of Tihia are also caused by the presence of the same clays, probably resulting from geothermal fluids beneath the site.

A second line of measurements passes northward through the saddle between Kakaramea and Tihia. These values are in the intermediate to low range, with only one value of apparent resistivity greater than 100 Ωm. In general, at similar elevations, lower values were found on the north-facing slopes than those on the south. Fig. 2 also shows a systematic variation of direction of E field polarisation along this line, which are consistent with a lateral change of resistivity in this vicinity. These data suggest that the resistivity boundary lies just north of the divide and the field underlies the northeast facing slopes of Kakaramea and Tihia. The apparent resistivity values that were obtained south of the divide are lower than those that mark the boundary elsewhere and leave open the possibility that some geothermal fluids may drain to the south at depth.

On the northeastern slopes of Kakaramea, the pattern of apparent resistivities (Fig. 2) is not as regular as is found over flat lying geothermal fields. Such lateral resistivity variations may be caused by the nature and disposition of the andesite flows and partly by topographic effects. High resistivities could be expected in near-surface young andesites, which have not been exposed to thermal fluids rising from a deep thermal reservoir. Andesites at other nearby sites may have been thermally altered by rising gases and have had their resistivity reduced, Thus the intermediate values of resistivities do not necessarily indicate the absence of an underlying thermal reservoir.

7. CONCLUSION

The occurrence of the Tokaanu-Waihi geothermal field beneath the flanks of Kakaramea makes the task of delineating the field more complex than with the majority of the TVZ geothermal fields which occur in flat terrain. At the high elevations, the geothermal fluids are deeper than on the lower slopes, which reduces the resistivity contrast that may be expected. Although the extent of geothermal fluids can be defined more easily at low elevations, the fluids at low elevation may derive from outflow of geothermal waters from higher elevation, and may be underlain by cooler conditions. Our best estimate of location of the Tokaanu-Waihi field is given approximately as the region outlined by the 20 Ωm contour in Fig. 4.

To define the extent of the geothermal system more accurately at higher elevations will require a greater density of measurement points to help distinguish the various flow patterns that may exist. It is possible that other techniques may help define the system. In particular the extent of thermal alteration of the andesite cone caused by the geothermal fluids may be defined by aeromagnetic data recently collected. Similarly additional MT data will better define the deeper structure. Ideally these should be interpreted together.

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