TONGARIRO-TOKAANU RESISTIVITY STRUCTURE FROM MAGNETO-TELLURIC SOUNDINGS

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SUMMARY - Magneto-telluric resistivity soundings have recently been made at 23 sites between the Tongariro and Tokaanu geothermal fields, in the central North Island of New Zealand. The resistivity structure, derived from layered interpretation of the soundings, suggests that these fields are not hydrologically connected. They are separated by a graben or depression, which has a maximum depth of about 1.2 km near Lake Rotoaira, and is filled with Tertiary mudstone, sandstone, siltstone and Quaternary volcanic alluvium. The basement is high resistivity greywacke. Gravity modelling supports this interpretation. Both Tongariro and Tokaanu geothermal fields have high-standing, low-resistivity (<5 ohm-m) steam condensate aquifers, associated with intense hydrothermal clay alteration. Both fields also have northern outflow structures, and evidence of increasing resistivity at depth where higher temperature alteration may be present

1. INTRODUCTION

Tongariro and Tokaanu geothermal fields are located between Lake Taupo and Mt Ruapehu in the central North Island of New Zealand. They are both situated in steep terrain associated with andesite volcanoes (Tongariro - 1960 m and Kakaramea - 1300 m). Access by vehicle is very difficult and this has limited their coverage by traditional DC resistivity traversing methods. Between these geothermal fields, which are about 20 km apart, there is another andesite cone (Pihanga) and a low-lying area occupied by Lake Rotoaira (560 m).

Geophysical studies reported by Hochstein and Bromley (1979), and later by Walsh *et al* (1998), depicted the resistivity structure of Tongariro as consisting of a low resistivity condensate layer overlying a more resistive vapourdominated reservoir. In the 1979 model, a thin hot brine layer was also inferred to exist at about sea level. An underlying high resistivity basement was interpreted to indicate unaltered hot rock. The 1998 resistivity model was constrained by only 10 shallow penetrating DC soundings and 4 MT soundings, of which two (dating from 1976) had a very limited measurement frequency range. However, the overall resistivity structure is considered to be consistent with the hydrological and geological setting of a condensate-capped, vapour-dominated system.

The evidence for magmatic fluids, the isotopic characteristics of the discharged steam (Giggenbach, 1996) and the history of volcanic eruptions from Tongariro craters also support classification of this field as a volcanic geothennal system.

Tongariro fumaroles have high boron concentrations, but there are no chloride fluid discharges around the flanks of Tongariro, despite steep topographic relief. This was initially puzzling, and led to conjecture about whether the high chloride and boron springs at Tokaanu, 20 km to the north, might be the surface expression of an outflow from Tongariro. Such outflows are commonly found around geothermal systems with elevated volcanic settings in the Philippines and Indonesia. Giggenbach (1996) discredited the idea of a link between Tongariro and Tokaanu on geochemical grounds. However, the Tokaanu springs do have geochemical similarities to the Waihi and Hipaua thermal features to the west. Furthermore, the primary upflow for the Tokaanu-Waihi system is interpreted by Severne (1998) to be closest to Hipaua, based on gas and isotope data.

Resistivity surveys conducted previously in the Tokaanu-Waihi area (Banwell, 1965, Reeves and Ingham, 1991, Risk *et al*, 1998) confirm that the Tokaanu, Waihi and Hipaua thermal features belong to a single geothermal field with an area of at least 25km^2 (<20 ohm-m). A video infra-red survey of the thermal features contained within this area is reported in Bromley and Mongillo (1991). The parent reservoir fluid for this system is interpreted to have a chloride content of 2400 mg/kg and temperatures of 240-260°C based on Na-K-Mg geothermometry (Severne, 1998). The deep fluids undergo boiling at about 190°C. The resulting, more concentrated brine, rises directly to the surface at Tokaanu (370 m asl) resulting in discharges with up to 3300 mg/kg chloride. Steam and gas rise to the surface at Hipaua, and produce acid condensates which mix with groundwaters. Mixtures of bicarbonate-enriched groundwaters and deep chloride fluids feed the lower elevation dilute springs at Waihi Village, and the thermal bore waters in Tokaanu township.

There are no deep boreholes in either the Tokaanu-Waihi or the Tongariro geothermal fields to test these conceptual hydrological models. However, other geophysical surveys, including gravity, magnetic, seismic, microearthquake and resistivity, have contributed significantly to our current understanding of the geological, thermal and structural setting in this area.

2. GRAVITY

Interpretation of residual gravity anomalies (Stern, **1979)** implies the presence of a graben or depression, infilled with predominantly low density material, linking the caldera of Lake Taupo with the andesite volcanoes in Tongariro National Park and the sediment-filled Wanganui Basin to the south. This link was first suggested by Rev. Richard Taylor in his **1855 diary**. It was first modelled by staff of the DSIR NZ Geophysical Survey, (in Gregg **(1960)**, p **93)** as a narrow graben within greywacke basement centred beneath Lake Rotoaira (down to -600m RL) and the volcanic centres of Tongariro and Ruapehu (down to about sea level). In the vicinity of Lake Rotoaira, the **1960** model for the graben used an average density contrast of **-0.47** Mg/m^3 for the infilling strata. Tertiary sediments within the Taupo-Tongariro graben are predominantly early Pliocene to late Miocene in age, with average densities of about 2.2 Mg/m^3. This is deduced from Hunt **(1980)** using samples collected near Karioi (south of Mt Ruapehu) and near Moerangi (NW of Tokaanu).

From gravity measurements, Sissons **(1981)** determined in-situ densities of the upper 300 m of andesitic rock overlying the Tokaanu tunnel, that passes through the flanks of Tihia, north of Lake Rotoaira. His best fitting model showed densities increasing with depth from **2.14** to about **2.6** Mg/m^3 at **300** m depth. Paterson **(1980),** in a report on the geology of the western diversion tunnels for the Tongariro Power Development, showed that a layer of Tertiary marine sediments, exposed to the west, is mantled near Lake Otamangakau by about 100 m of Quaternary ring plain deposits (alluvium and lahar) derived from Tongariro. A similar or thicker sequence of low density volcanic debris is likely to have helped infill any depression in the vicinity of Lake Rotoaira. Additional useful information on the likely thickness of Tertiary marine sediments through this graben comes from interpretation of a seismic refraction survey across the southern ring plain lahars between Ruapehu and Karioi (Sissons and Dibble, **1981).** Basement greywacke **(Vp=4.95** km/sec) lies at elevations of about 200 m (± **100** m asl). This is overlain by about 500 m of inferred Tertiary sediments with velocities of 2.2 to **3 km/s**. The overlying lahar deposits have slightly lower velocity (2 km/s) and thicken towards Ruapehu.

Recent gravity measurements undertaken by Zeng **(1996)** across the Tama Lakes saddle between Tongariro and Ruapehu show a negative residual gravity of **-15** mgals at the top of this saddle, compared with about -20 mgals at Lake Rotoaira. Zeng's 2D modelling of the Tama Lakes gravity profile, when combined with magnetic modelling, shows a volcanic sequence of andesite lavas **(2.58** Mg/m^3) and pyroclastics (1.8 Mg/m^3) overlying greywacke basement at about 500 m asl, but cut by a trench of andesite. However, it was noted that the density difference between greywacke and andesite lava is small. This makes it difficult to reliably determine the basement depth. MT data shows the presence across the Tama Lakes profile of moderately low resistivities (30 to **60** ohm), in a layer at about **400** m to **1.5** km depth. **Although** Zeng **(1996)** interprets this to indicate fractured andesite, saturated with mineralised fluid beneath the volcanic vents at Tama Lakes, it is also possible that a layer of Tertiary mudstones could be contributing to this moderately low resistivity anomaly.

Following a review of all the information summarised above, a simple two-dimensional model was constructed using the residual gravity data (from the GNS database) along a NW-SE profile through Lake Rotoaira The end points of the profile are located on greywacke. Figure **1** shows the model, and the fit between observed and calculated gravity values. The simplest model consists of a graben about **1.2 km** deep and 25 km wide, of average infill density 2.2 Mg/m^3, within greywacke basement of **2:67** Mg/m^3. The actual basement interface, rather than smoothly dipping, is more likely to be a sequence of steps along NNW trending normal faults, that straddle Lake Rotoaira. Gregg (1960) shows a number of these normal faults that are of late Quaternary age indicating that the graben has continued to subside long after deposition of Tertiary sediments. Therefore the upper few hundred metres of the graben infill is likely to contain recent volcanic alluvium (eg. lahar deposits) or shallow lacustrine sediments, whereas the deeper parts of the graben probably contain older beds of marine sediments. In the absence of subsurface samples from this graben infill, there is no reliable basis for differentiating between these layers solely on the basis of density.

3. MICRO-EARTHQUAKE STUDIES

Since **1986,** several swarms of micro-earthquakes, with magnitudes typically less than 3.2, have been located within the upper crustal rocks of the **Tokaanu-Waihi** geothermal field and on the northern flanks of Tongariro geothermal field (Hochstein et al, **1995,** Walsh et al, **1998).** The average focal depth is about **5** km which is presumably within greywacke basement. These swarms have been linked to the possibility of intermittent magma injection into dykes within the brittle crust. Such injection would provide a source of heat that might sustain or progressively enlarge these geothermal systems. Some young volcanic extrusions **(<10** ka) have occurred

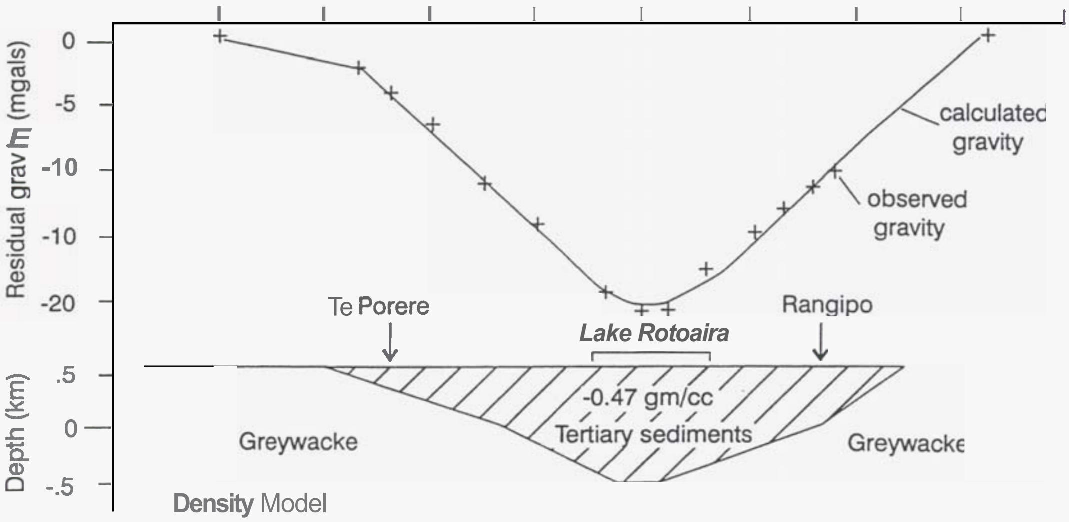

Figure 1. Gravity interpretation of a NW-SE profile through Lake Rotoaira, showing a 2D model of low density sediments infilling a graben.

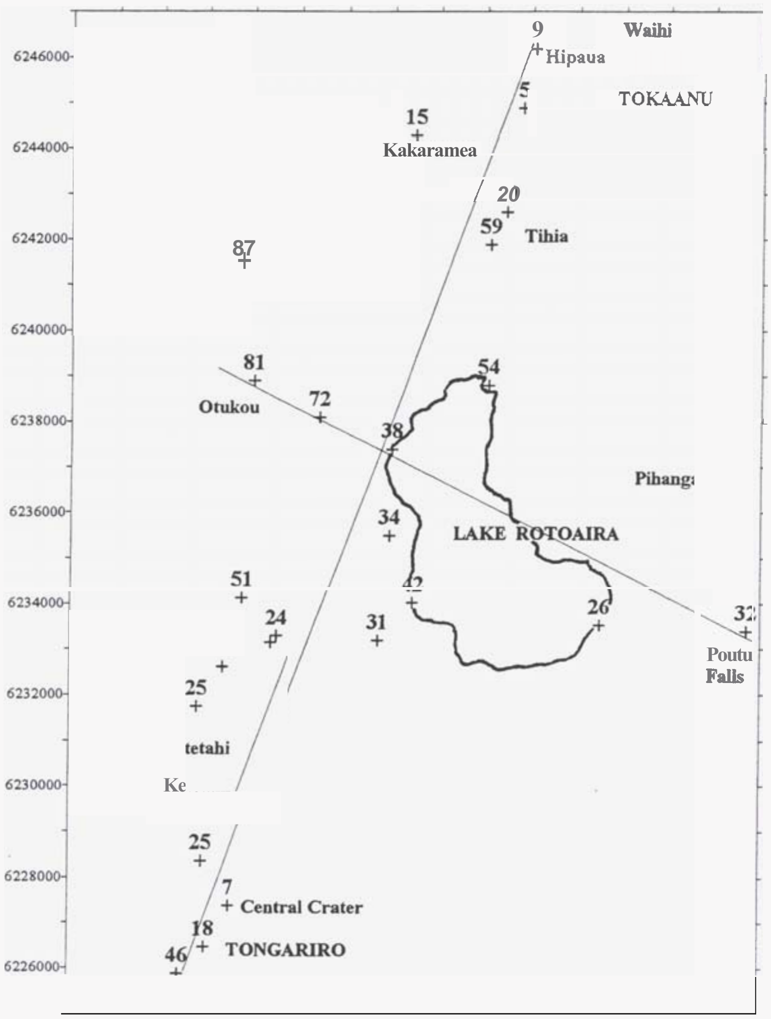

Figure 2. Location map of magneto-telluric soundings in the Tongariro-Tokaanu area, labelled with rotational invariant apparent resistivities at 8 Hz frequency. Lines show cross-section locations.

adjacent to Tokaanu (Kuharua and Maunganamu), as well as at Tongariro ("e Mari crater was historically active between 1869 and 1896). So it is possible that magma injection in basement fractures is still occurring. The subsurface seismic velocity structure in this area is poorly known. A model used for determining earthquake hypocentres, that assumes high velocity greywacke (6 km/s), underlying about 2 km of low velocity sedimentary and volcanic formations (3.5 km/s), is consistent with the graben model described above.

4. MAGNETO-TELLURIC RESISTIVITY

Early magneto-telluric soundings made in the vicinity of Tongariro were limited to low frequency (long period), deep penetration measurements. For example, a sounding by Marriot (1969), located a few kilometres west of Lake Rotoaira, showed increasing apparent resistivities (30 to 150 ohm-m) at periods of 2 to 300 seconds. This is consistent with high resistivity greywacke underlying a thick surface layer of moderate resistivity (30 ohm-m). MT soundings reported by Hochstein and Bromley (1979) on Tongariro were also limited to long period data (T >3 seconds) and showed increasing resistivities at depths of several kilometres. However, resolution of the resistivity structure in the upper 2 km was hindered by the lack of higher frequency data.

Later soundings conducted at Tokaanu by Reeves and Ingham (1991), covered a wider frequency spectrum (1 kHz to 0.1 Hz) but were limited to the low lying north-eastern edge of this field. These soundings were considered suitable for penetration depths of about 100 to 1000 m. One-dimensional modelling of the 13 soundings showed a sharp eastern resistivity boundary (possibly fault controlled) in the vicinity of the Tokaanu hydro-electric power station, and a deeper north eastern boundary near the Tongariro River. Within the geothermal field, resistivities of about 3 ohm-m are underlain by higher resistivities.

50 Hz magneto-telluric resistivity measurements, with an uncontrolled artificial source (power lines), have also been made at various locations at Tokaanu and Tongariro (Risk et al, 1998). Unfortunately, many of the sites are affected by proximity to the power line source (creating "near-field" effects). They also have linearly polarised electric and magnetic fields, making tensor analysis meaningless. The orientations of the resulting scalar resistivities (maximum E field direction) can be influenced by both the source orientation and any local resistivity anisotropy or topography. A guide for the minimum distance to the nearest source to avoid "near-field" effects is four times the skin depth (D), where D = 503 SQRT (Resist./Freq.) (Zonge and Hughes, 1988). In the Tokaanu low resistivity area (5 ohm-m), a suitable minimum distance (600 m) is achievable, however, on the flanks of the andesite volcanoes (50 to 250 ohm-m) minimum distances of 2 km to 5 km can be much harder to achieve. For example, six of the new MT soundings (Figure 2) that are located within 2 km of live power lines around Lake Rotoaira, have anomalous 50 Hz resistivities (2 to 30 times higher than values at adjacent frequencies, for the E-field dipole oriented parallel to the source).

4.1 New MT Soundings

New tensor magneto-telluric resistivity soundings have been conducted over the past two summers in the Tongariro-Tokaanu area. Locations of the 23 sites are shown in Figure 2. A frequency range of 8 kHz to 0.02 Hz was recorded, allowing a theoretical penetration depth range (for 20 ohm-m) of about 20 m to 10 km. In practice, however, weak natural signal strength, particularly in the frequency bands from 0.1 Hz to 1 Hz, and 1 kHz to 3 kHz, limits the penetration depth range. Where data is of poorer quality (low signal to noise ratio) the interpreted resistivity models are less well constrained. Sometimes, longer site occupation times helped to improve data quality (by stacking and averaging). Most sites were occupied for about three hours.

Measurements were made with orthogonal horizontal arrays of electric field dipoles (Ex, Ey) and magnetic coils (Hx, Hy, Hz). The data acquisition was accomplished with a Zonge GDP-32 receiver. This receiver uses cascade decimation, stacking, and averaging of fourier transformed cross and auto-power spectra of the 6^{th} and 8^{th} harmonics, to obtain amplitude and phase measurements of the electric and magnetic fields. Using robust processing mode, data are accepted or rejected according to coherency and outlier limit tests: typically a coherency limit of 0.7 and outlier rejection limit of two times the median. For all stations, a notch filter to attenuate 50 Hz (and its odd harmonic frequencies) was applied to the incoming signals. This prevents saturation at the gains needed to record natural source data. A signal pre-conditioner (SC-8) also pre-amplifies the electric field voltages, and filters out RF frequencies and SP drift. Resistivities and phase differences are calculated using standard Cagniard formulae, and plotted against frequency for interpretation in terms of layered resistivity models.

One dimensional modelling of all soundings is undertaken using an iterating best-fit algorithm to minimise the RMS residuals between observed and calculated resistivities, and phase differences. The iteration is weighted towards the average values with the lowest standard deviations, and is also repeated numerous times fi-om different starting models to determine the overall uncertainty in the optimum layered model (Monte Carlo method).

Two-dimensional cross-sections are compiled from the layered models. These are shown in Figures 3 and 4. Full 2D inversion of these cross-sections is not justified because the sounding locations, being designed for regional coverage, are not spaced closely enough to properly constrain any 2D inversion of resistivity boundary structures. However, soundings located close to boundaries inferred fi-om the cross-sections often reveal evidence of 2D or 3D effects (diverging resistivity curves at low frequencies). In these cases, the layered interpretation at depth, is treated cautiously.

Static-shift distortion effects (significant parallel displacement of Ex or Ey oriented resistivity curves) were observed at six stations, and divergence of curves at low frequency at four stations. Shallow DC resistivity measurements (AB/2 of 25 m or 50 m) were made at many of the sites, using the orthogonal Ex and Ey dipoles. These generally showed isotropic resistivity near the surface. There was no correlation between shallow DC resistivity distortions and either static shift or curve divergence effects, suggesting that the MT distortion effects originate from lateral resistivity inhomogeneity outside the array, or at depths greater than 25 m. For example, soundings located at the centre of Tongariro's South Crater and Central Crater, on flat terrain, both showed strong divergence at frequencies below 2 Hz (see Fig. 5). The lowest resistivities, in each case, were oriented in the Ex direction (110"). This could be interpreted to indicate the presence of a strong 2D resistivity anomaly, at least 500 m from the soundings, and oriented approximately NNE. A likely candidate structure is the linear vent which probably underlies the hydrothermally active Red Crater and Emerald Lakes, on the SE side of Central Crater.

4.2 MT Resistivity Interpretation

The cross-sections in Figures 3 and 4 illustrate the interpretation of most of the soundings in this study. Figure 2 shows the location of the two section lines, from Tongariro to Tokaanu, and from Otukou to Poutu Falls. Also plotted on Figure 2 are the apparent resistivities (rotational invariant) at 8 Hz frequency for each station. This represents an effective penetration depth (for 30 ohm-m) of about 700 m.

A low resistivity layer of 2 to 5 ohm-m occurs within Tongariro, between Red Crater and Ketetahi fumarole areas. The top of this layer is at about 1500m elevation, matching Ketetahi acid sulphate springs. This layer is probably caused by acid-condensate fluids, with associated intense hydrothermal alteration, perched above a vapour dominated geothermal system. The resistivity structure at depth is complicated by the 2D effects described above, however there is a suggestion of a resistive basement (approximately 100 ohm-m) at about –1800 m (RL) beneath North Crater and rising to the north. A small outflow of diluting condensate fluids (15 ohm-m) is interpreted to occur downslope of Ketetahi, but these fluids never reach the surface, and appear to diminish towards the base of the volcano.

In the depression occupied by Lake Rotoaira, the sounding interpretations suggest a sequence of lithologies, based on their probable resistivity signature: (a) near-surface andesite lavas (150-300 Ωm), (b) Quaternary volcanic alluvium/lahars and Tertiary sandstone/siltstone (40-50 Ωm), (c) Tertiary mudstones (23-28 Ωm), (d) greywacke basement (500-750 Ωm). These resistivity values are consistent with many in-situ measurements made on such lithologies.

Although no constraints on depth were applied in the resistivity modelling process, the similarity in the level of the interpreted greywacke basement fiom MT soundings and from gravity modelling is quite convincing (see Figures 1, 3 and 4). Both models independently show basement at about -600 m (RL), centred in a graben beneath Lake Rotoaira. The inferred Tertiary mudstone layer that sits on top of basement has a relatively uniform resistivity (23-28 ohm-m) and a thickness of up to 1 km. Interpretation of this layer as mudstone is supported by several in-situ resistivity measurements on Tertiary mudstone to the south of Tongariro National Park. These include values of 22 and 23 ohm-m (DC soundings at Utiku and Taihape in Dawson et al, 1982).

Interpretation of the five new MT soundings between Kakaramea, Tihia and Hipaua suggests that the Tokaanu geothermal system extends further west than was implied from the previous shallow resistivity measurements (Risk et *al,* 1998). A low resistivity anomaly (4 ohm-m) encompasses Kakaramea, borders the Tihia saddle, and reaches an elevation (about 900m) similar to the highest thermal features identified by Bromley and Mongillo (1991). This suggests the presence of a perched layer of condensate fluid and intense hydrothermal alteration, as at Tongariro. The "condensate" layer of low resistivity dips steeply to the north. At elevations of about 400 m, the low resistivities are probably caused by deep chloride water mixing with *steam*-heated groundwater, and outflowing to the springs at Waihi Village beside Lake Taupo (360 m). Similar low resistivity (3 ohm-m, from Reeves and Ingham, 1991) occurs near the Tokaanu high chloride springs to the east. A resistive basement (nominally 100 ohm-m) occurs beneath the two soundings near Hipaua, but this is based on relatively noisy data at low frequency. Additional soundings, with better quality data at frequencies

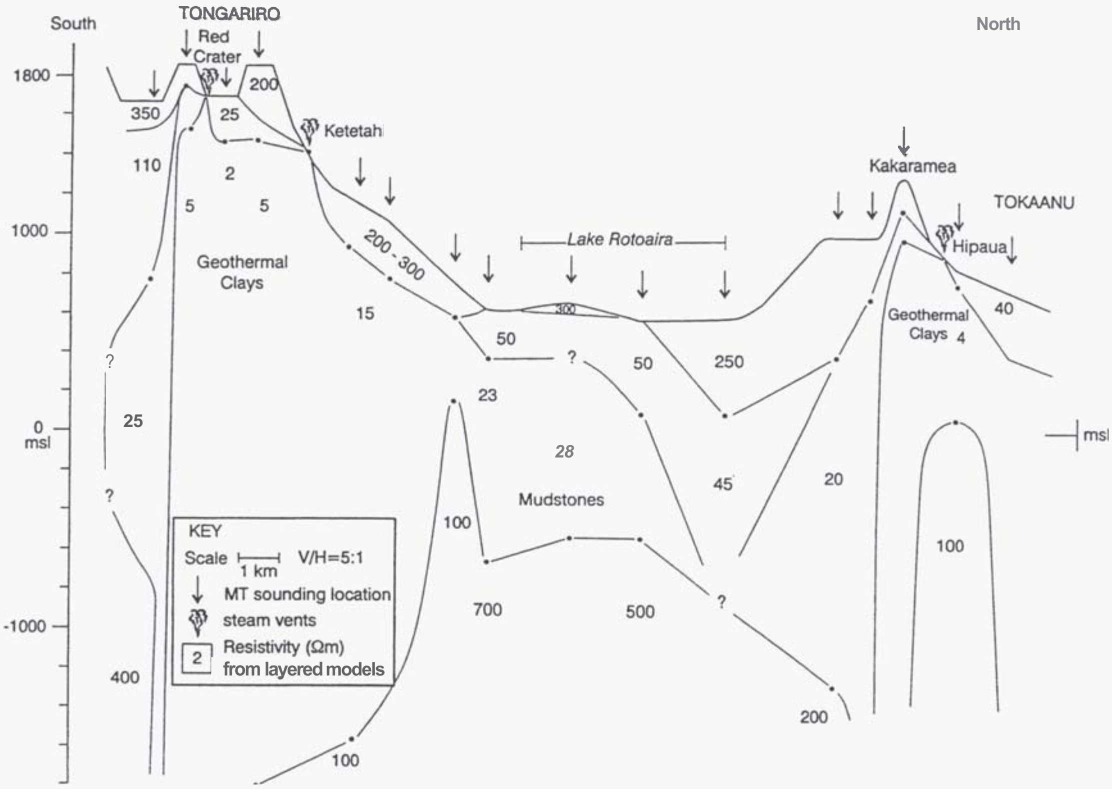

Figure 3. Layered resistivity interpretations from MT soundings along Tongariro-Tokaanu cross-section.

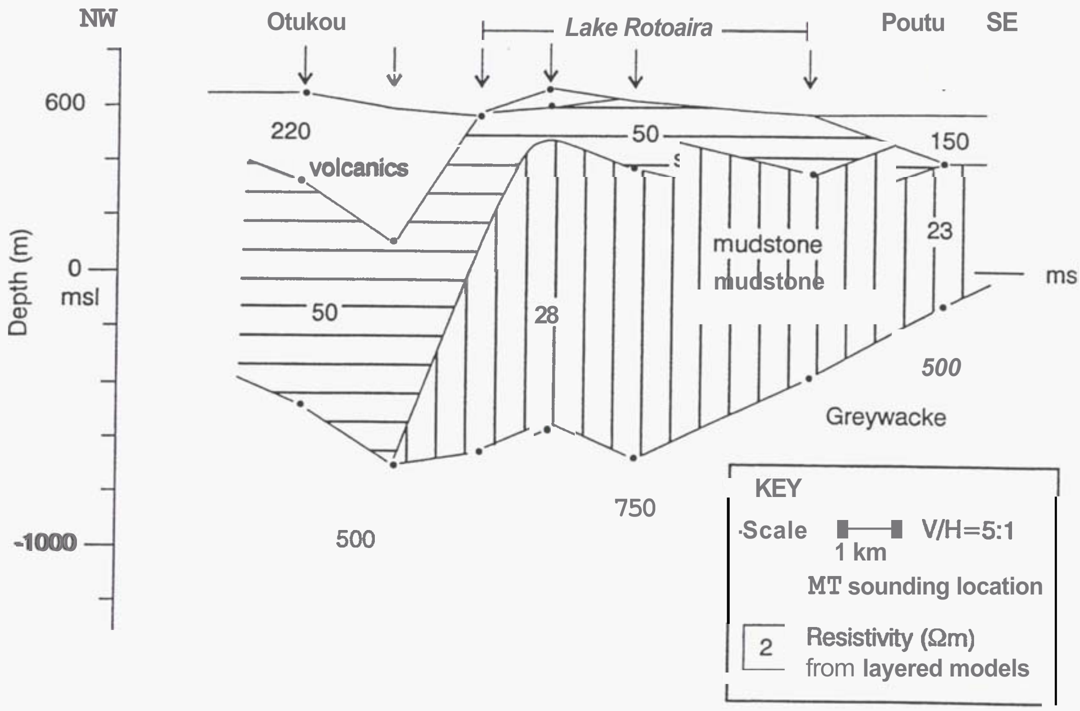

Figure 4. Layered resistivity interpretations for MT soundings along a NW-SE cross-section through Lake Rotoaira. Compare this with central 10 km of gravity cross-sections in Figure 1.

below 1 Hz, are needed in this area to improve the resistivity model of this part of the Tokaanu geothermal field. It is possible that the higher resistivity, at about sea level or deeper, is caused by a transition to higher temperature alteration (chlorite, illite, quartz) within a productive geothermal reservoir. This is mantled by a low resistivity cap of intense clay alteration (smectite, kaolinite, etc). Such a model is commonly observed in explored geothermal fields hosted in volcanic lithologies.

Finally, despite the probable existence of a connecting graben, it is clear from Figure 3 that there is no direct connection between the low resistivity anomalies of Tongariro and Tokaanu geothermal fields. Geophysical data therefore supports the geochemical evidence that the two fields are distinct.

5. CONCLUSIONS

Magneto-telluric resistivity soundings, recently conducted in the Tongariro-Tokaanu area, have been interpreted to indicate that these two geothermal fields are not hydrologically connected. There is no continuous low resistivity layer (<10 ohm-m) between them, so it is inferred that the high chloride fluids at Tokaanu do not originate fi-om Tongariro.

The two fields are underlain by a NNE trending graben, which is centred beneath Lake Rotoaira, where it is about 1.2 km thick. Basement is interpreted to consist of high resistivity greywacke (500-750 ohm-m), and the graben infill mostly consists of a thick sequence of Tertiary marine sediments (predominantly mudstone, with an average resistivity of 25 ohm-m). Overlying layers of sandstone, siltstone and Quaternary volcanic alluvium (lahars) have a resistivity of about 50 ohm-m. The infill material is adequately modelled using an average density of 2.2 Mg/m^3.

The Tertiary sediments are probably Late Miocene to early Pliocene in age and may extend south from Turangi, beneath Tongariro, to beyond Ruapehu. It is suggested that a layer of these mudstones, 500-1000 m thick, may be contributing to the moderately low resistivities beneath Tama Lakes and to a low velocity, low resistivity structure beneath the southern flanks of Ruapehu (Bromley, 1996).

The Tongariro geothermal system has an extensive high standing (1500 m asl), low resistivity (<5 ohm-m) layer, caused by intense hydrothermal clay alteration from a steam condensate cap over a vapour dominated system. A small condensate outflow extends north from Ketetahi, but doesn't reach the surface. Two-dimensional distortion effects on MT soundings within Tongariro Central and South craters may be explained as lateral resistivity anodes beneath the hydrothermally active Red Crater fumeroles. Higher resistivity layers observed in some Tongariro soundings at depths below sea level may be caused by higher temperature alteration (chlorite, illite, quartz) or low permeability, unaltered hot rock.

The Tokaanu geothermal system also has a high standing, low resistivity layer (<4 ohm-m) interpreted to indicate steam condensate fluids and clay alteration particularly beneath the eastern flanks of Kakaramea and the northern side of Tihia. This western extension of the resistivity anomaly has increased the known area of the field to about 30 km^2. Underlying higher resistivities in some of the Tokaanu MT soundings may also indicate higher temperature conditions (less conductive clays). Additional MT soundings are recommended in the south western sector of the Tokaanu geothermal field to better elucidate these resistivity structures, and help refine the conceptual model of the reservoir.

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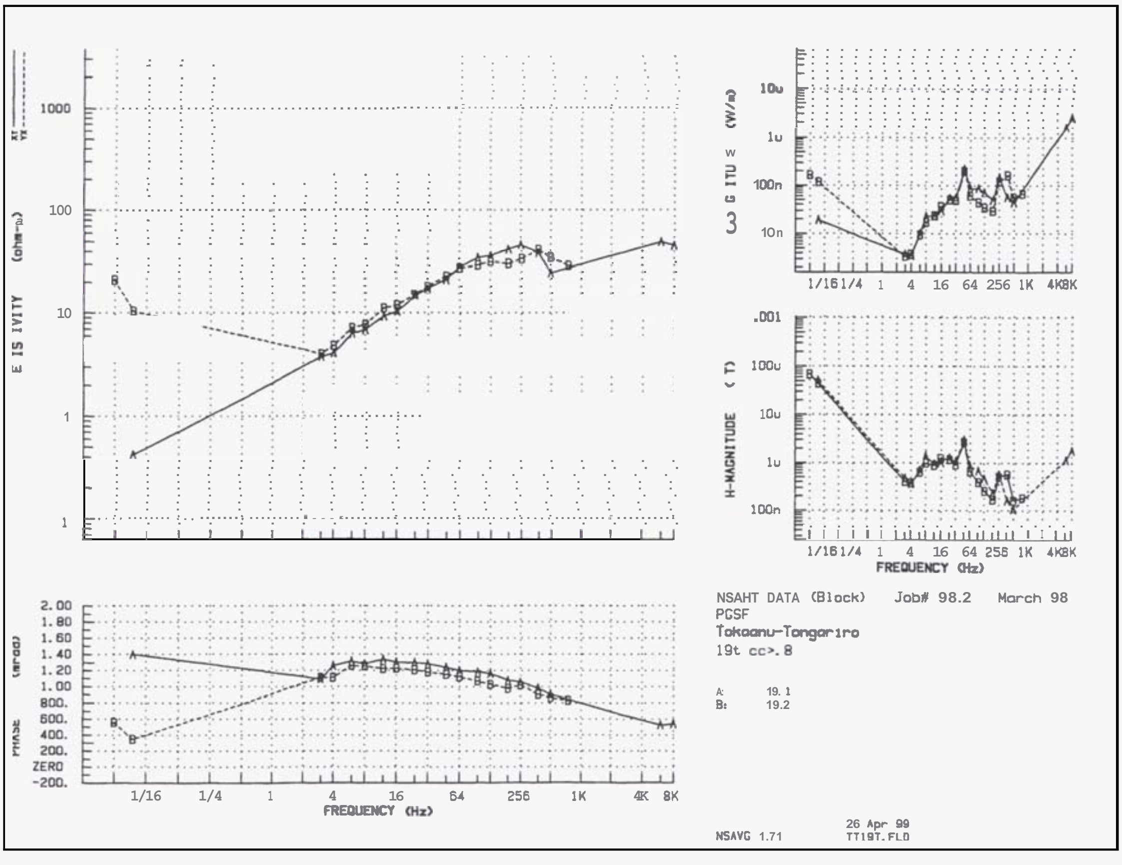

Figure 5. Example of MT resistivity sounding data at Site 19 (Tongariro Central Crater), using a correlation coefficient filter >0.8. Curves A and B are oriented magnetic east and north.