# WAIKITE – TE KOPIA: THE MISSING LINK?

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## SUMMARY

Recent geophysical surveys conducted in the vicinity of Waikite and Te Kopia suggest the likelihood of a deep connection between these two geothermal fields. The existence of such a link could have important implications on future development options and on environmental management plans for neighbouring resources. The surveys included an airborne video thermal infrared survey of Waikite and Te Kopia, which revealed in detail a much larger number of surface thermal features than had previously been recognised. In addition, closely spaced tensor *CSAMT* soundings were conducted along profiles at three locations between the two fields. Interpretation of these soundings suggests that the fields are connected by a broad corridor of low resistivity below about 600 m depth. Supporting evidence is provided by a set of DC resistivity measurements (using tensor bipole-quadripole and Schlumberger arrays) obtained at the same locations, and by a low level aeromagnetic survey conducted for mineral exploration purposes in 1986.

## 1.0 INTRODUCTION

The geophysical surveys described here form part of the first stage of a multi-disciplinary geothermal investigation of the Waiotapu geothermal field (located about 30 km south of Rotorua) and its adjacent hydrothermal systems, including Waimangu, Reporoa, Waikite and Te Kopia. The overall goal of this research is to investigate geothermal processes in unexploited systems, and to evaluate the degree of interaction between neighbouring protected and unprotected geothermal systems. During the first year attention has focused on the Wailcite and Te Kopia fields (see Figure 1). Infrared surveys were conducted over the Waikite and Te Kopia thermal features to establish an accurate map of their extent. The chemical characteristics of these features were also investigated (Glover, 1992) and specialised resistivity measurements were made between the two fields to investigate a possible connection.

The thermal infrared video imagery was collected using two helicopter-mounted infrared scanners. Surveys were flown after dusk on the 6th and 27th of March, 1992, using a satellite global positioning system (GPS) for navigation control. These surveys were funded by the Waikato Regional Council, with a contribution from Crown research funds. The main purpose of the infrared surveys was to safely obtain data on the location, size and intensity of the surface thermal features at Waikite and Te Kopia, which had not previously been mapped. In addition, a baseline dataset (in the form of a videotape) was established for comparison with future infrared surveys to monitor change in surface thermal activity. Any such change could be an important environmental impact consideration for future management of these resources.

The resistivity measurements consisted of Controlled Source Audio-Magnetic Telluric (CSAMT) soundings, supported by DC measurements, at sites distributed along the base of the Paeroa Fault *scarp* between the Waikite and Te Kopia fields. Resistivity soundings and regional traversing measurements (nominal AB/2 spacings of 500 and 1000 m) had previously been collected throughout this area, and the results (Geophysics Division, DSIR, 1985 and Macdonald, 1965) suggested that there was no connection between the Waikite and Te Kopia fields. However, as noted by Healy (1974), the chemistry of the fluids discharged from the two systems is very similar. There is also more recent evidence from a low level (60 m terrain clearance) aero-magnetic survey, conducted in 1986 (Merchant, 1990), to suggest that there may be a broad corridor of demagnetised rock, possibly resulting from hydrothermal alteration, linking the two fields, along the base of the Paeroa fault *scarp.* Any proven connection between these geothermal fields could have important implications on future management options for either source, therefore, a more detailed resistivity study of this region between the fields is well justified.

The *CSAMT* resistivity technique has been used widely overseas for mineral, petroleum and geothermal studies, and has been applied to some epithermal gold prospects in New Zealand, but has not previously been tested for use in New Zealand geothermal investigations. The natural field magneto-telluric technique was used near Broadlands (Ingham, 1990, Whiteford, 1975) with some success, but a lack of telluric signal strength at frequencies near 1 Hz (critical for geothermal studies) often limits the method. Use of a controlled some has the potential of overcoming this limitation. The Waikite-Te Kopia connection hypothesis provided an opportunity to appraise the CSAMT technique in a New Zealand geothermal setting. For comparison purposes, additional DC resistivity measurements were taken at the same locations as the CSAMT soundings, using standard tensor bipole-quadripole and Schlumberger traversing arrays. As part of the appraisal, the limitations caused by signal to noise ratio, and the effects of typical electrical noise sources, such as high voltage power lines and electrically-earthed pipework, were also investigated.

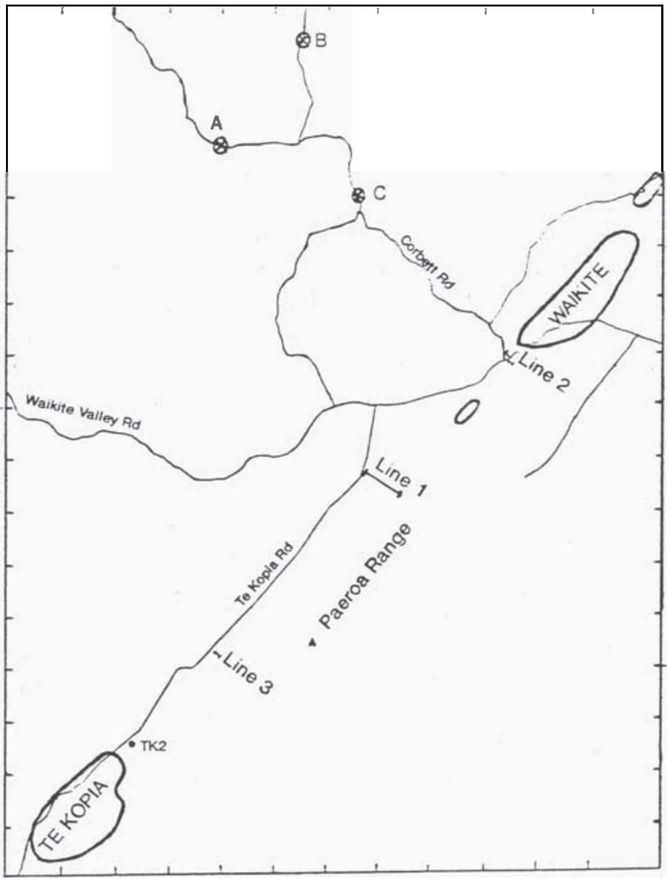


Figure 1: Location map showing Waikite and Te Kopia geothermal areas, CSAMT lines (1 to 3) and current electrode locations (A to C). Map base from Sheets U16 and U17, NZMS 260 series, 1 km grid.

## 2.0 THERMAL INFRARED SURVEY RESULTS

Both infiared survey flights (6/3/92 and 27/3/92) commenced about an hour after sunset to minimise residual solar heating effects and absorption of IR by early morning fog or steam. The first flight was abandoned after 1 hour, however, because of low cloud moving in from the northwest. In both cases, the typical helicopter speed was 125 to 150 k/hr, and the nominal ground clearance was 600 m (maintained by auto pilot using a radar altimeter in the first survey, and barometric altimeter in the second survey). Navigation during the first flight was achieved using a portable Magellan NAV 1000 PRO GPS system, with locations downloaded to a PC at 5 to 10 second intervals. Improved navigation during the second flight resulted from the use of a high performance Garmin GPS with locations downloaded to a PC every 2 seconds. Flight lines were spaced 150 m apart in two NE trending blocks to fully cover the Te Kopia and Waikite thermal features. Additional thermal features were also over-flown during the two surveys. These included parts of the following areas: Ngatamariki, Orakei Korako, Waiotapu, Waimangu, Rotomahana, Tarawera, Opaheke, Reporoa, Ohaaki, Rotokawa and Tauhara. The infrared instruments consisted of a FLIR 1000A and Inframetrics 525, detecting at wavelengths of 8 - 12 pm. Data was stored as grey-scale imagery on VHS-PAL videotape. Further details of the instrument specifications are given in Bromley and Mongillo (1991). The FLIR instrument gain was set to 58 and level to 22, while the Inframetrics temperature range was set to 20°C, based on previous experience. Ground truth temperature measurements were made of water surface temperatures at calibration sites distributed throughout the area. This information will be used to help calibrate the digitized infrared imagery when comparing repeat surveys.

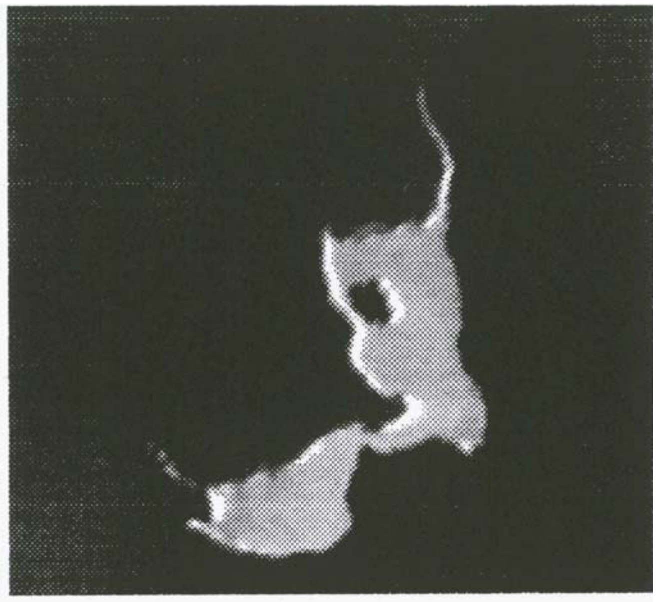

Figure 2: Puakohurea thermal lake (Waikite), temperature 31°C to 47°C, 150 m x 150 m contrast-enhanced infrared image, viewed SW.

PC-based image processing software, based at Wairakei, was used to generate and enhance a total of 45 images of selected scenes (approximately 300 m by 150 m) digitized from the infrared video tapes. All the images were filtered with a uniformly weighted 3 x 3 spatial filter to reduce image noise and vibration effects. The grey-level images were then pseudo-coloured and contrast stretched to enhance anomalies of interest. An example of a grey-scale enhanced image is given in Figure 2. The resulting imagery can be used to provide a detailed and comprehensive map of the geothermal surface activity, and also establishes a basis for comparison with future IR surveys to monitor changes in thermal features. The survey covered an area of more than

5 $km^2$ at Te Kopia and 15 $km^2$ at Waikite, at nominal ground resolutions of about 2 $m^2$. It revealed an elongated band of intense thermal activity, which extends along the NW side of the Paeroa Range. Many previously unmapped thermal features within this area have now been accurately delineated using this infrared technique. In particular, large areas of steaming ground have effectively been mapped along the steep and inaccessible portions of the Paeroa Fault scarp at Te Kopia and Waikite.

## 3.0 RESISTIVITY RESULTS

CSAMT is a frequency-domain electromagnetic sounding technique (Zonge and Hughes, 1992) that has developed from the standard magneto-telluric (MT) method, but uses a controlled current source consisting of a fixed grounded bipole, ideally located at least four skin depths away from the sounding locations. This allows the application of MT equations derived for a plane wave source. The controlled source provides a dependable stable signal, resulting in higher precision and more efficient data collection. For tensor CSAMT, two perpendicular current sources are generally used, and vector measurements made of electric and magnetic fields at a range of frequencies. At Waikite, however, we introduced the use of a triangular set of 3 current bipoles, and applied a least squares procedure to calculate the tensor resistivity components. This procedure has become standard practice for DC bipolequadripole tensor resistivity surveys in New Zealand, and its advantages are now well recognised. Furthermore, the use of the same set of 3 current bipoles for both CSAMT and bipole-quadripole measurements facilitated a direct comparison of the results from the two methods. Details on the use of tensor analysis for DC bipolequadripole surveys can be found in Bibby (1986) and for standard magneto-telluric surveys in Kaufman and Keller (1981).

CSAMT measurements were recorded using a state-of-the-art multifunction 8 channel receiver (GDP-16) generously made available to us for this trial survey by Zonge Engineering and Research Organisation Inc. The source waveform (provided by our GGT-30 generator) was a square wave of about ± 20 amps at frequencies of 4 Hz to 4 kHz. The minimum useable frequency (which gives the maximum penetration) was determined by the source to sounding spacing (6 to 10 km), which in turn was limited by the received signal to noise detection limit, using the maximum available current. Therefore, we found that the practical penetration depth range at Waikite for the CSAMT soundings was from surface to about 1.2 km. The DC bipole-quadripole measurements had much deeper probing depths of about 4 to 10 km.

The CSAMT soundings were located at 20 m intervals along 3 profile lines oriented perpendicular to the Paeroa Fault scarp (see Figure 1). Results from the longest (700 m) line are given in Figure 3 as contoured pseudo-sections of Cagniard resistivities and static-corrected phase resistivities. The Cagniard resistivities are simply calculated from the ratio of the magnitudes of the electric and magnetic fields, but the phase resistivities require some explanation. They have been calculated by integrating the phase differences between the electric and magnetic fields, and then normalising them to a non-static-affected resistivity value at an intermediate frequency (256 Hz). The resulting pseudo-section removes most of the shallow static-effect distortions that are obvious in the Cagniard resistivity plot. The cause of the large (two orders of magnitude) static-effect distortion is a disused pump with an electrically earthed metal water pipe, in a stream located near station 18. As a consequence of New Zealand's (somewhat unusual) system of linking electrical earth to neutral, this pipe is therefore directly connected to every other earth connection in the district, which includes a large water pump near one of the current electrodes. The static effect, then, is caused by a small portion of the generated current passing through the neutral wire of the power lines and into the ground surrounding the water pipe, which acts as a secondary source. The resulting frequency-independent galvanic distortion is localised, however, to within about 50 m of the water pipe.

A characteristic of shallow static effect distortions of the electric field is that they are independent of frequency, and appear to persist to great depths. Therefore DC resistivity measurements should also be susceptible to static effects. The DC bipole-quadripole resistivities along line 1 demonstrate this little known fact with a distortion of about 1 order of magnitude near station 18. (Note that CSAMT resistivities are calculated using the square of the electric field, hence the CSAMT static distortions are squared relative to DC distortions).

Another common problem with CSAMT surveys is interference from high voltage power lines. Data from line 2, located near the Waikite Springs and about 700 m from transmission power lines, illustrated this problem at frequencies above 250 Hz which were not protected by the standard 50 Hz and 150 Hz notch filters.

Interpretation of the CSAMT soundings using a one dimensional modelling program resulted in similar 4 layer structures for all 3 lines between Waikite and Te Kopia. An example is given in figure 4. Here, Cagniard apparent resistivities are plotted against the log of the period, using data calculated from harmonic analysis of the received square wave signals. This modification of the standard processing procedure makes use of the first 4 odd harmonics of the fourier decomposed signals as well as the fundamental frequency, which results in five times the number of data points on the sounding curves for the same duration of recording. The calculated curve for the best fitting layered model is also shown, along with phase differences in milliradians. Modelling of the basement resistivity and depth has been guided by using the much deeper penetrating DC bipolequadripole resistivities. These are also plotted on the sounding curve at a nominal period of 8 seconds which is determined by assuming that the frequency domain skin depth is equivalent to the AB/2 probing depth. Note, however, that DC resistivities are not

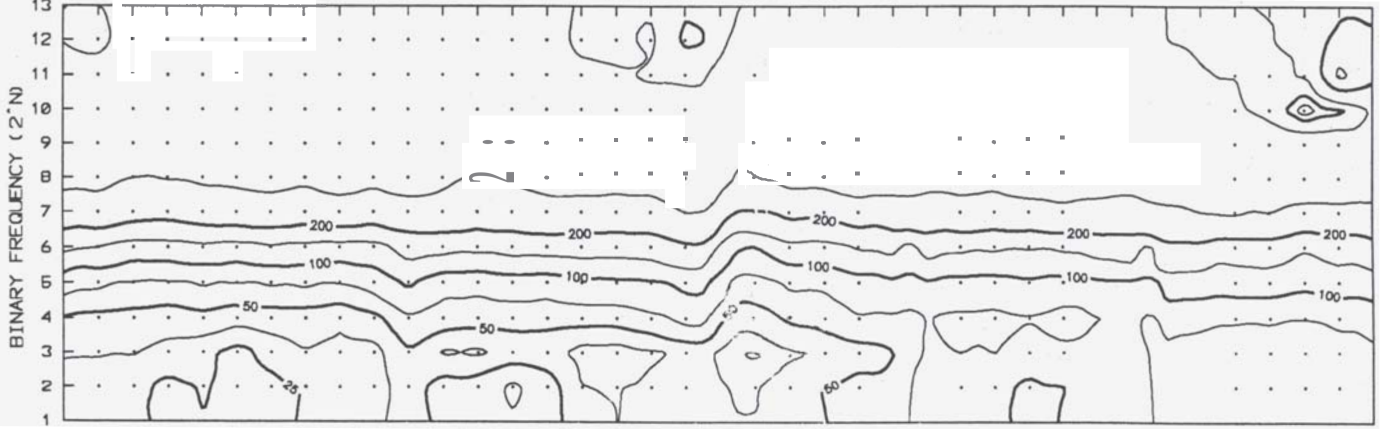


Figure 3: Line 1 CSAMT contoured resistivity pseudo sections. Measurement locations at binary frequencies ($2^2$-$2^{12}$ Hz)

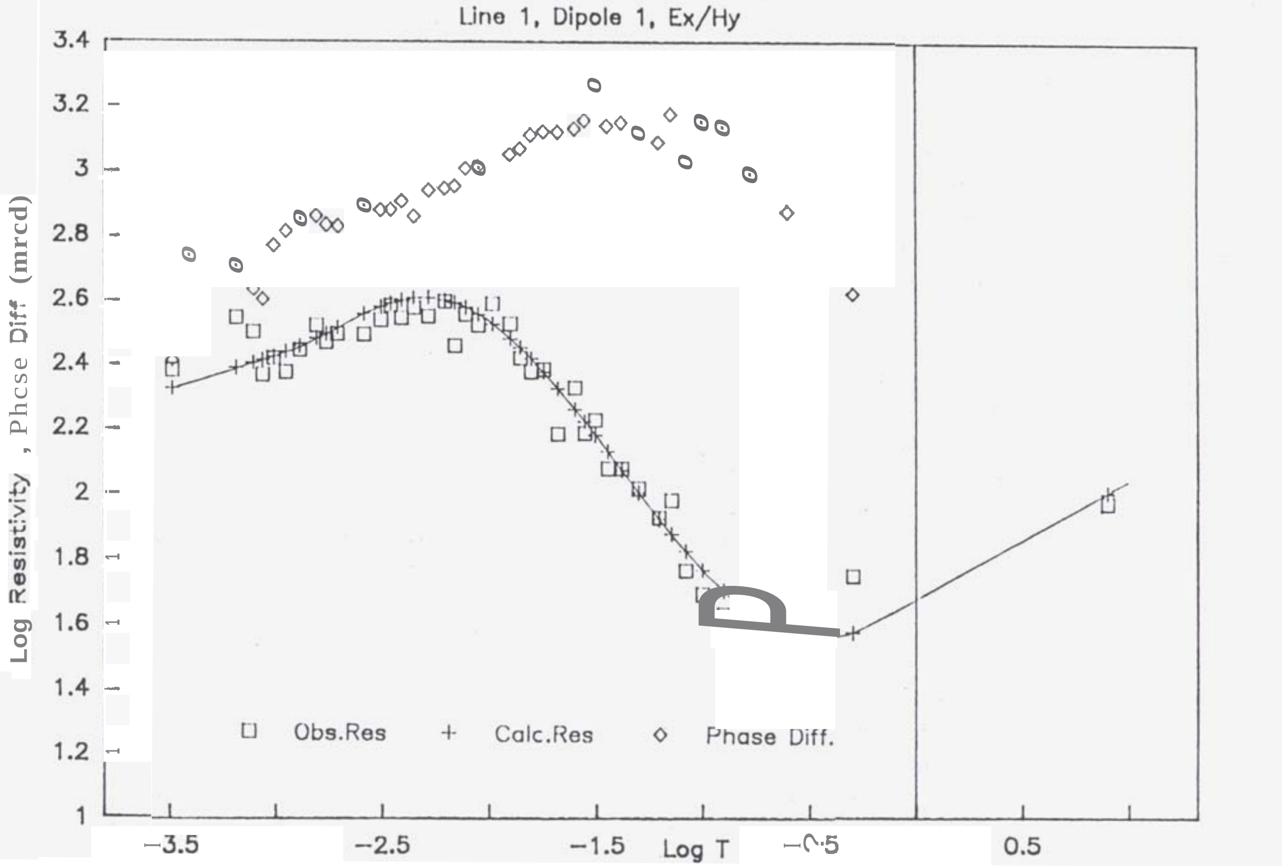


Figure 4: Typical harmonic analysis CSAMT sounding, showing observed Cagniard resistivities and phase differences, together with calculated resistivity curve from layered model. DC resistivity also plotted at a period of 8 seconds.

strictly equivalent to CSAMT resistivities, because they are calculated using measured electric fields and assumed current densities, rather than measured electric and magnetic fields. Also, it is assumed in this approach that a 1 dimensional layered earth model is valid beneath the sounding stations and the current electrodes. Because of these assumptions the modelled basement depth and resistivity must be treated with caution. Along line 1 the interpreted layered structure can be summarised as follows:

| | Thickness (m) | Resistivity (ohm-m) | |
|---|---|---|---|
| 1) | 40-100 | 90-150 | (saturated tuff) |
| 2) | 500-750 | 400-500 | (tuff/ignimbrite) |
| 3) | 200-500 | 5-10 | (hydrothermal clays) |
| 4) | basement | >200 | (ignimbrite/rhyolite) |

Without the constraint of the DC data, the modelled low resistivity layer can range in value from 2 to 10 ohm-m and the basement is not resolved. Support for the suggested geological interpretation, given above, is shown in figure 5, where a comparison is made of a sounding model from line 3 and the geological logs of Te Kopia borehole TK2 (from Bignall, 1991), located about 2 km to the SW. Clearly the low resistivity layer is related to a sequence of hydrothermally altered and permeable rhyolites and tuffs below 650 m depth.

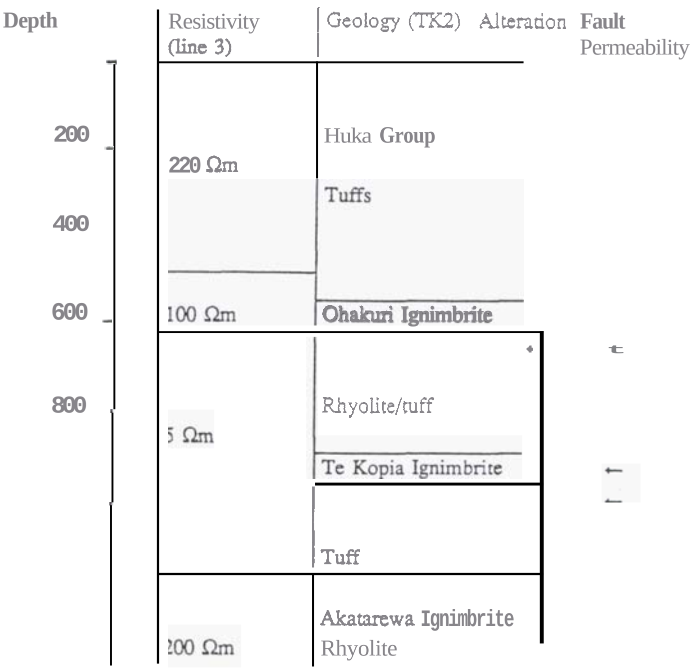


Figure 5:

Tensor analysis of the bipole-quadripole resistivities show some interesting differences between the 3 lines. After rotation of the coordinate axes to maximize the diagonal elements of the tensor, the resulting maximum and minimum resistivities (RMAX and RMIN) differ by about 25% for lines 1 and 2, suggesting that the structure here is predominantly one dimensional, but with a small two dimensional overprint. At line 3, however, the maximum resistivity is twice the minimum, suggesting a dominating two dimensional structure. Despite the similarity of the sounding curves from the three lines, there are clearly differences in the preferred orientations of the current flow caused by the subsurface structure. The azimuths of the RMAX axes are 130°, 60° and 90" for lines 1 to 3 respectively.

Tensor analysis of the CSAMT data from a representative station (No. 13) on line 1 revealed azimuths for the rotated (diagonalised) tensor axes of 124° to 130° for all 10 frequencies, consistent with the DC results. The shapes of the two rotated CSAMT sounding curves (referred to in the literature as TM and TE or perpendicular and parallel modes) are consistent with those of a two-dimensional structure, consisting of a fault bounded, deeply buried, low resistivity layer.

Additional deep Schlumberger-array resistivity measurements were also obtained at selected stations on line 1 to check the results of the CSAMT soundings, which had indicated the existence of a thick layer of low resistivity below about 600 m depth. Eight current electrodes were established along Te Kopia Road, and measurements obtained using nominal AB/2 spacings of 600 m, 1200 m, 1800 m and 2400 m. The resulting partial soundings were interpreted using a layered model that matched the CSAMT models (less than 10 ohm-m at 600 m depth). It was obvious from these sounding curves that the previous Schlumberger traversing data (AB/2 of 500 m and 1000 m) collected along Te Kopia Road did not have adequate penetration to detect the deep low resistivity connection between Waikite and Te Kopia.

## 5.0 CONCLUSIONS

Recent helicopter-borne video infrared surveys conducted over the Waikite and Te Kopia fields have mapped large areas of thermal ground that were previously unknown or poorly mapped because of access difficulties. A database now exists that can be compared with future IR surveys to monitor changes in surface thermal activity.

Interpretation of CSAMT soundings located on three profile lines distributed between Waikite and Te Kopia geothermal fields suggests that there exists a broad zone of low resistivity below about 600 m depth, linking the two fields. Such a link is supported by evidence of a broad magnetic low along the NW side of the Paeroa Fault and by the geochemical similarity of discharged fluids. It was not previously detected by regional resistivity traversing surveys because of inadequate penetration. The low resistivity layer appears to correlate with a layer of hydrothermally-altered and fractured rhyolite tuffs logged in borehole TK2. Support for the interpretation of this low resistivity layer was provided by Schlumberger array DC resistivity measurements at selected locations using nominal AB/2 spacings ranging from 600 m to 2400 m. Other resistivity studies in the neighbouring Broadlands-Wairakei area (eg. Ingham 1990) have also been interpreted Using a linking low resistivity layer at moderate depths (0.5 to 1.5 km). It is possible that this may be a widespread feature common to many of these closely spaced TVZ geothermal fields. Assuming that these links originate from hydrothermal alteration, then the implications in terms of possible long-term fluid and pressure interference affects between fields should be addresed.

Tensor bipole-quadripole resistivity measurements were made at most of the CSAMT sounding sites, using the same triangular set of three current bipoles. These provide useful comparative resistivity information, and help constrain the deep resistivity model if 1D layering is assumed. Tensor analysis of both the bipole-quadripole and CSAMT data, using a least squares procedure and axis rotation, results in a set of tensor invariants and rotation parameters that reveal apparent anistropy in the resistivity data caused by two-dimensional structure that varies with location.

An important additional objective of this CSAMT study was to investigate advantages, disadvantages and constraints of the method in determining the resistivity structure in New Zealand geothermal areas. One of the most common problems is the frequency independent "static effect", and this was dramatically demonstrated on line 1 (near station 18). A 100 m wide resistivity distortion of up to two orders of magnitude in CSAMT data, and one order of magnitude in DC data, results from an earthed metal pipe, which is connected through the powerlines to another earth near the current electrodes. With CSAMT data, however, the static effect can be removed by integrating and normalising the phase differences (which are static free).

Other problems include high voltage power line noise contamination (demonstrated on line 2), and depth penetration limitations, indirectly caused by signal to noise constraints as soundings are conducted further away from the current source, in order to meet the requirement for plane wave propagation at lower frequencies. The conclusion from this study is that the CSAMT method may be considered appropriate for conducting soundings in most New Zealand geothermal areas to depths of about 1.0 km. With appropriate equipment, a large number of sounding locations can be occupied relatively efficiently, because the method uses a small measurement array, which provides logistical advantages. CSAMT is most useful where lateral resolution is important, or where a thick cover of high resistivity material overlies a low resistivity anomaly of interest.

## ACKNOWLEDGEMENTS

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