ELECTRICAL IMAGING OF SHALLOW GEOTHERMAL AQUIFERS USING FIXED LOOP TEM SOUNDINGS IN THE OTUMUHEKE SPRING AREA, TAUPO, NEW ZEALAND

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ABSTRACT

Delineating potential fluid pathways of geothermal fluids through near-surface geological strata can help to provide a better understanding of the interaction between geothermal fluids and shallow groundwater aquifers. It can also help to explain the presence or absence of surface geothermal features and potential sub-surface hydraulic links between groups of surface features.

The fixed loop transient electromagnetic method (TEM) was used to map the near-surface (<200 m) electrical structure in detail around the Otumuheke Spring area, Taupo, New Zealand. The vertical component of the TEM signal was modelled in 1-D for 308 sites. The resulting 1-D electrical profiles compare favourably with existing conceptual models and available geological data. They provide an insight into the possible pathways of the source fluids through the near-surface strata for some geothermal surface features in the Otumuheke Spring area.

INTRODUCTION

The types of surface thermal features of geothermal systems (e.g., hot springs, fumaroles, hot ground) will vary depending on a range of geological and hydrological factors. Factors that can control the location, type and size of a feature can include structural features such as faults; the permeability of geological strata; physical conditions of the geothermal system such as depth, pressure and temperature; availability of fluids; chemistry of the fluids; and the aquifer structure above the geothermal up flow. Clay alteration is common along pathways of geothermal fluids, causing potential low resistivity anomalies (Ussher et. al, 2000), provided that the geothermal fluids are hot enough and the host rocks are amenable to alteration.

TEM is a resistivity sounding technique that is suited to resolving the lateral and vertical shallow resistivity structure of the earth. The method involves measuring the decay of the vertical magnetic field over time from a pulse of electric current applied through a loop of wire (Nabighian and Macnae, 1991). Results of this technique depend on factors such as the amount of current used in the loop, the size of the loop, the sampling interval, style of TEM (e.g., In-loop, fixed loop, etc.) and the resistivity structure of the earth. The technique has been widely used to map aquifers in sedimentary environments (Fitterman, 1987; Meju et al., 2000; Auken et al., 2003) and for geothermal exploration (Spichak and Manzella, 2009). Fixed loop TEM (Nabighian and Macnae, 1991) is a style of TEM that uses a stationary large loop with a mobile receiver that makes measurements inside and outside of the loop. This technique is used extensively for mining (e.g., Craven et al., 2000). In-loop TEM measurements are made with the receiver in the middle of the loop. Taking measurements at different locations requires moving both the loop and the receiver so that they are central over the measurement point. In-loop TEM soundings are less affected by current channelling and current gathering effects which may occur around strong conductors as may be present in geothermal areas.

This paper seeks to use fixed loop TEM measurements to delineate near-surface resistivity structures. By interpreting these structures in terms of the geothermal regime, we can better understand the near-surface geothermal interactions.

STUDY AREA

The Tauhara – Wairakei Geothermal Field lies on the edge of Taupo Township and is conveniently divided by the Waikato River into the 'Wairakei' and the 'Tauhara' areas on the western and eastern side of the Waikato River respectively. A geological and hydrological link exists between the Wairakei and at least the western part of the Tauhara Geothermal Fields (Rosenberg et al. 2010, Bromley, 2009; Allis, 1983).

The Wairakei Geothermal Field has been producing electricity since 1963, and changes to geothermal features in the area are well documented (Bromley, 2009). Effects seen over time due to the development include: a reduction in reservoir pressures, increases/decreases of steam-heated surface features, loss of chloride springs, reduced flows of geothermal water at the surface and reduced groundwater aquifer levels. Features in the Tauhara Geothermal Field that have become inactive include the AC and Kathleen Springs, Crows Nest geyser and the Witches Cauldron Spring (Figure 1). These are all located in the western part of the field in the Otumuheke Spring area. The area also contains active thermal features such as the Otumuheke Spring and weakly steaming ground.

The near-surface geology in the Otumuheke Spring area consists of volcanic and lacustrine deposits (Rosenberg et al., 2009). This includes superficial surface deposits (post-Oruanui and Taupo pumice) up to 60 m thick, underlain by the Oruanui Formation (pyroclastic volcanic deposits) between 50 m – 100 thick, and then the Huka Falls Formation (HFF) lacustrine deposits (mudstones, sandstones and siltstones). All of the formations contain aquifers and aquatards. The HFF caps the geothermal system.

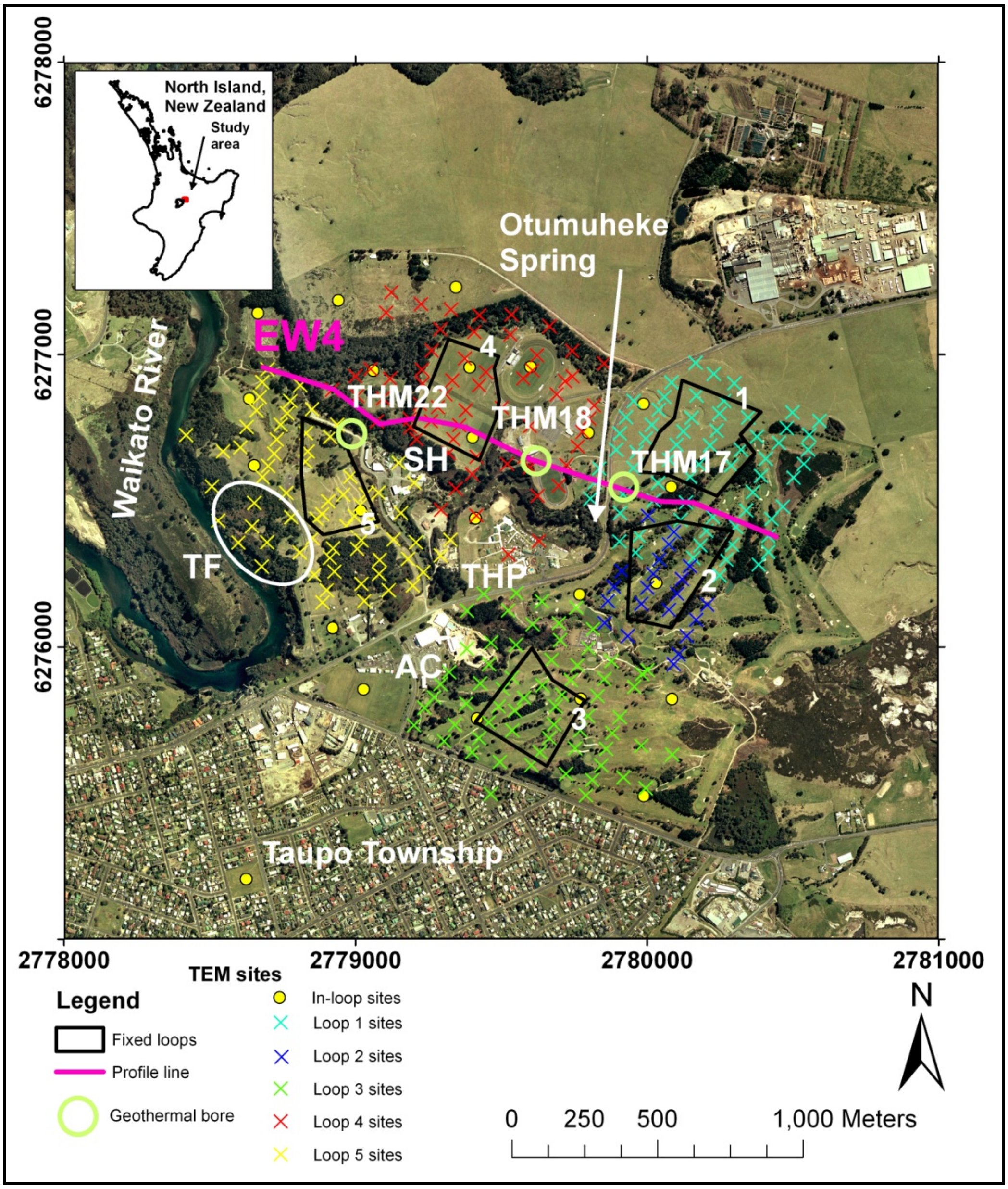

Figure 1. Location of the survey area with TEM sites and geothermal bores. AC = AC Baths, SH = Spa Hotel, THP = Taupo Holiday Park, TF = location of extinct thermal features.

METHOD

Fixed loop surveys were carried out at 5 different locations in the Spa Park/Taupo Golf Course area between 13 September and 01 October 2010. A quasi-rectangular loop with a nominal loop size of ~300 m was used to transmit the TEM source signal The cable used for each loop contained four independent strands that were connected to achieve a four loop source. The loop was connected to a Zonge GGT30 transmitter that applied a current of 12 A at 16 Hz.

A Zonge GDP32 receiver connected to a TEM-3 magnetometer was used to collect data at a total of 308 sites. At least two blocks of data averaged over 2048 cycles were collected at each site at 25 time intervals between 49.7 µs and 12.19 ms. Data were generally collected in lines with a nominal station spacing of 50 m along each line, although this varied depending on the terrain and available time. A GPS location was measured at each site. Three duplicate stations using different loops were recorded to assess models between loops.

In-loop TEM data were collected using a Zonge GDP32 receiver connected to a TEM-3 magnetometer. The GDP32 was connected to a NT-20 transmitter which supplied a source signal using a current of 2A at 16 Hz to a 100 m loop. Typically three blocks of data averaged over 4096 cycles were stored in the GDP32. Data were collected between June 2010 and August 2010.

Both fixed loop and in-loop TEM data were pre-processed using Zonge software and imported into the IX1D™ software for quality control and modelling. Data at each site were visually inspected for off-scale and noisy data. Off-scale data were masked so that they were not used in the modelling process. Noisy sites were removed from database and not used for modelling and subsequent interpretations.

Both layered and smooth 1-D models were generated for all sites. Smooth models were calculated using either Occam's inversion (Constable, et al, 1987) or Ridge Regression (Inman, 1975). Layered models were calculated using Ridge Regression with a starting model based on the smooth model. Initial modelling parameters were changed until suitable model curve fits to the data and/or suitably low RMS errors were obtained. Models from the in-loop data were primarily used to control models for the fixed loop models. 1-D models were generally generated in profile lines to ensure consistency of models across short distances. Data are presented along profile lines that span the study area and include models from sites from multiple loops. In-loop data are not presented in this paper. Profiles are compared to publically available geological data from the geothermal explorations bores (THM22, THM17 and THM18) in the area of the survey. Small errors may be introduced when data from the geothermal bores is projected onto some profiles as the bores do not fall exactly on any of the profiles.

Presentation of the data using these methods assumes:

- Anomalous coupling effects between the source signal and the ground is negligible for each loop.
- Current channelling effects (Spies and Parker, 1984) are negligible.

RESULTS AND DISCUSSION

Data were collected from 308 fixed loop sites, with 1-D models generated for 286 sites. In general, there were good correlations between the layered and smooth models. Modelled resistivities are highly variable, ranging from greater than 1000 Ωm to less than 0.1 Ωm. However, resistivities are generally low (<50 Ωm) indicating a relatively conductive environment over the study area. This was to be expected given the geothermal activity and the nature of the sediments with the study area.

A northwest – southeast resistivity profile (Figure 2) shows:

- Zones of very high resistivities (>300 Ωm) occur near the ground surface down to about 60 m. These zones are not continuous across the profile. The high resistivity zones are probably associated with Taupo Pumice deposits. This resistivity signature is seen in most profiles. The shapes of these zones is consistent with mantling of the Taupo Pumice on the surface, filling "old" valleys of the Oruanui Ignimbrite as is seen in road cuttings (M Rosenberg, personal communication 1/7/2011).
- Other than the Taupo Pumice, there is little correlation between the electrical resistivity profiles and the known geology. In fact, large resistivity differences occur within geological units. Resistivity differences within geological units can be caused by several factors that could include; variation of sediment within the unit, clay alteration, the presence of geothermal fluids, silica / calcite deposition with the strata or cold water intrusion.
- Resistivities are generally higher in the western part of the profile compared to the eastern part. This suggests that there is generally less geothermal alteration of the sediments in the west. The cause of a lateral high resistivity zone at about 250 m RL on the western boundary of profile (Figure 2) is unclear.
- Two lateral very low resistivity zones occur at about 300 m and 380 m relative level (RL) in most profiles. The upper low resistivity zone (~380 m RL) probably represents an aquifer that has had geothermal fluids in it at some stage. The elevation of the aquifer is at the geological boundary between the Oruanui Formation and the base of the Taupo Pumice. A geothermally influenced aquifer at this elevation can also be seen in the drilling losses/bore temperatures in THM17 (Figure 3) and observations from bore TH01/0 located approximately 200 m east of the line. TH01/0 is at a depth of 40 m (380 m RL) and was used to monitor hot groundwater water levels before the water level dropped; it now discharges small quantities of steam.

  The ~300 m RL elevation low resistivity zone is interpreted to represent a geothermally influenced aquifer in the Upper HFF and/or base of the Oruanui Formation. This is consistent with a zone of drilling losses encountered during drilling bore THM17 (Figure 3). It also corresponds to the depth of three geothermal bores in the study area (Spa Hotel, Taupo Holiday Park and one of the AC Baths bores, Figure 1). Lateral variations in the electrical resistivity of this aquifer occur along the profiles and could represent variations in geothermal alteration within the aquifer.

  The position of these aquifers is generally consistent with the conceptual model presented by Allis (1983) and Rosenberg et al. (2010) for this area.
- There is generally a good correlation between the laterial zones of very low resistivity zones in the Oruanui Formation and the UHFF, and an increase in down-hole clay abundance at bores THM22, THM17 and THM18 (Figure 2). Geothermal clays such as smectite, illite and chlorite occur with abundance in these bores (Figure 3).

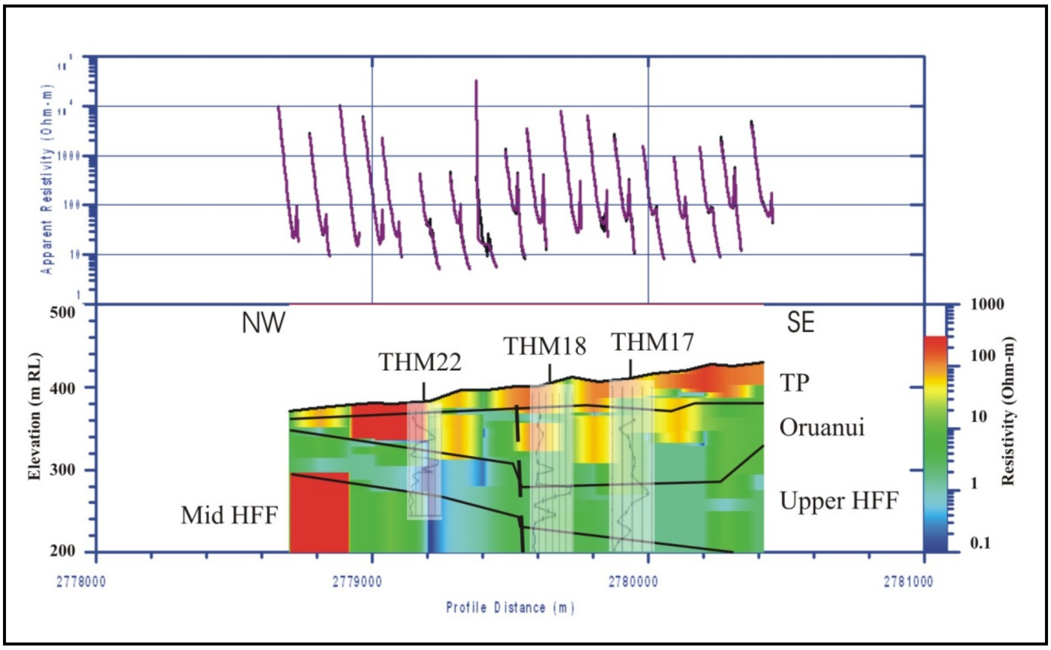

Figure 2. Northwest – southeast resistivity profile from the smooth model along profile EW4. The black near-vertical dashed line is an inferred fault from Rosenberg et al. (2010). TP = Taupo Pumice, HFF = Huka Falls Formation. Down-hole clay abundance (Rosenberg et al., 2009b) has been superimposed at each bore with percentage clay content increasing to the right. TEM site locations / model fits are above the profile.

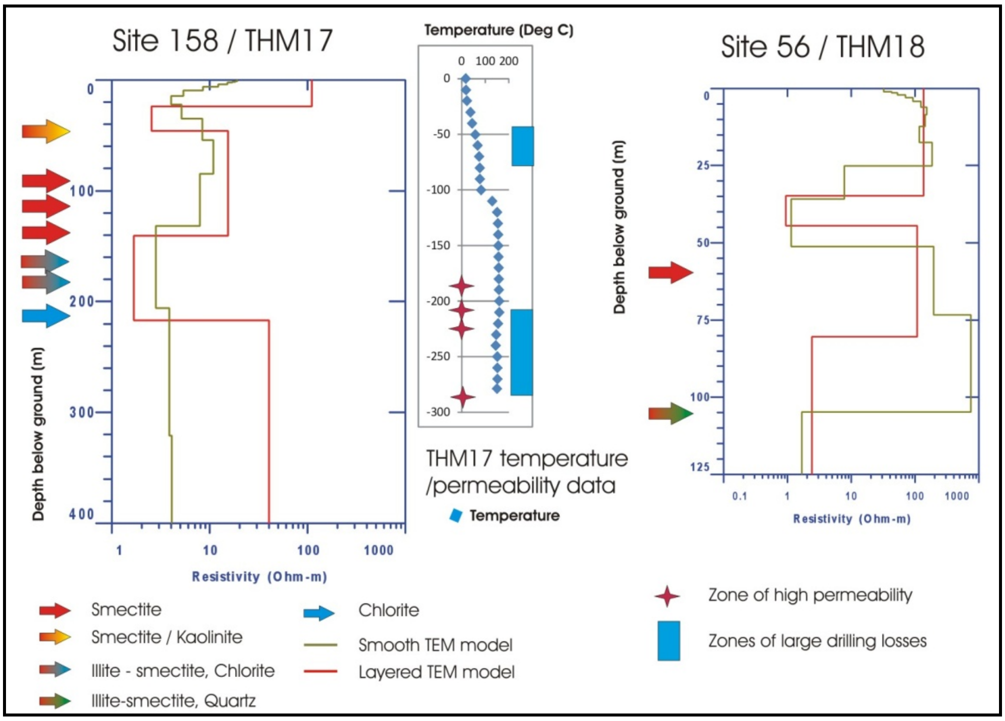

Figure 3. Comparison of resistivity models at sites 158 and 56 to geological data at bores THM17 and THM18 respectively. Clay content data is taken from Rosenberg et al. (2009b). Note that samples for clay analysis are only collected ad-hoc and not at regular intervals. Down-hole temperatures (4 week test) and permeability data for THM17 were obtained from Contact Energy (2009).

- The low resistivity anomaly close to THM22 could be an artefact of collecting data near a 3D structure and probably does not realistically represent a near-vertical resistivity anomaly. However, it may be possible that the inferred geological fault nearby (Figure 2) is real, and that this may be causing 3D effects at this site. This would require further investigation. It is also interesting to note that there is a strong lateral low resistivity zone at the top of the anomaly (at approximately 300 m RL at THM22, Figure 2) similar to what might be expected where an up-flow of hot fluids hits an impermeable boundary and is forced to flow laterally.

CONCLUSIONS

A detailed resistivity survey has been completed around Otumuheke Spring area using a fixed loop TEM survey with 1-D modelling of the results. Resistivity profiles of the top 200 m show good correlations to exploration bore data in the area and are also consistent with previous conceptual models of the area.

Resistivities are highly variable within geological units, with very low resistivities probably associated with geothermal activity. More work is required to better delineate some resistivity anomalies and to investigate areas where 3D effects may be occurring.

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