Insights into the Waiotapu Geothermal Field using High Resolution SkyTEM Data

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ABSTRACT

Airborne Transient ElectroMagnetic (ATEM) geophysical methods enable high densities of data to be collected over large areas in an efficient manner. Resistivity models derived from the ATEM data enable high-resolution geological and hydrological structures to be interpreted in the near surface (approx. 400 m). We use ATEM data to interpret geological and hydrological features in the Waiotapu and Reporoa Geothermal Fields of New Zealand.

Selected cross-sections of resistivity models derived from ATEM data collected over the Waiotapu and Reporoa study areas are interpreted in terms of geology, hydrogeology and geothermal influences. Preliminary interpretations from the cross-sections show:

1. Good correlation between the ATEM data and the direct current resistivity maps of the spatial extent of low resistivity anomalies associated with the Waiotapu and Reporoa Geothermal Fields.

2. Good correlation between the locations of low resistivities and geothermal surface features.

3. A near-vertical low resistivity boundary on the western side of the Waiotapu Geothermal Field correlating with the mapped Ngapouri Fault. This implies a constrained permeable structure, or bounding structure.

4. Possible eastern extension of the Waiotapu Geothermal Field under the Kaingaroa Ignimbrite.

5. Correlation between some mapped active faults and low resistivity anomalies, indicating that faults (and specifically, which parts of the fault) could support geothermal fluid flow.

6. Abrupt resistivity boundaries may indicate either possible unmapped faults and/or geological boundaries.

7. Potential geothermal flows to the surface can be inferred in areas where low resistivity anomalies from the deeper part of the system can be traced to the surface.

1. INTRODUCTION

Airborne transient electromagnetics (ATEM) is a resistivity-based geophysical technique that uses aircraft to collect TEM data (e.g., Auken et al. 2017, Harrison et al. 2021). ATEM methods have traditionally been used in mineral and groundwater exploration because of their ability to map conductive bodies. However, the technique has been equally successful in identifying permeable paths for geothermal fluids in geothermal systems (e.g., Finn et al. 2021) given the generally strong conductive contrasts that are associated with high-temperature geothermal systems. Conductive anomalies in high-temperature geothermal systems can be caused by (or by combinations of) clay alteration, saline fluids and/or local geology (such as non-hydrothermal clays in mudstones).

The SkyTEM system is an ATEM system that has been used in New Zealand primarily for groundwater aquifer delineation (e.g., Rivas et al. 2020, Foged 2022). The system uses a helicopter to carry transmitter and receiver loops approximately 60 m off the ground (Figure 1). The helicopter flies along lines typically spaced 100–300 m apart and makes a measurement approximately every 30 m (depending on flight speed). Typical penetration depths for these measurements range from 100 m in conductive environments to 500 m in resistive environments. A detailed description of the SkyTEM system can be found in Sørensen and Auken (2004). Data is modelled (e.g., Auken et al. 2009; Viezzoli et al. 2008) to derive resistivity depth models at each measurement point. The high density of the resistivity models along lines enables resistivity contrasts to be accurately located both laterally (estimated 30–100 m) and with depth. This allows potentially detailed geological/hydrological interpretations to be made from the resistivity models where there are changes in resistivity laterally and/or with depth. This makes this technique very suitable for delineating shallow geological structures.

Figure 1: Typical SkyTEM configuration. The large loop below the helicopter contains both the transmitter and receiver loops. Photograph from SkyTEM.

2. STUDY AREA

The Waiotapu Geothermal Field (WGF) is located approximately 30 km southeast of Rotorua, New Zealand (Figure 2). The WGF has over 330 mapped geothermal surface features (Reeves et al. 2020) and is the largest of the major geothermal fields in the Taupō Volcanic Zone, having a natural heat flow of approximately 515MW (Seward et al. 2022). Geothermal resources at Waiotapu are valued by Ngati Tahu – Ngati Whaoa, who have long used the geothermal resources for cooking, preserving food, bathing, treating health conditions and trading kokowai (Reeves et al.

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2021). The WGF is classified as 'Protected' by the Waikato Regional Council, which means that only small-scale users of heat and fluid are allowed.

The geology of the WGF area is dominated by volcanic (ignimbrites and pyroclastic deposits) and sedimentary deposits (Wood 1994, Leonard et al. 2010, Downs 2020). The active geothermal area of the WGF is generally bound on the west by the NE/SW-trending Paeroa Range and associated NW/SW-trending faults and to the north by the dacite dome Maunga Kakaramea.

The southern boundary of the WGF butts up against the northern boundary of the Reporoa caldera. The caldera was formed during the eruption of the 0.3 Ma Kaingaroa Ignimbrite (Downs 2020) and now forms an approximately 130 km^2 largely topographically flat basin that has been infilled with sediments (Wood 1994, Leonard et al. 2010). Rhyolitic domes occur near the southern caldera margin and to the north of the caldera. Downs (2016) and Soengkono and Hochstein (1996) propose that the Kairuru Dome (Figure 3) may extend from the shallow subsurface into the centre of the caldera. Several small geothermal surface features occur in the centre of the caldera, with cooler springs also located at Golden Springs (approximately 6 km south from the other geothermal features). Bore (RP1) (Figure 2) drilled close to the central caldera geothermal features has temperatures of more than 200°C at 800 m below ground (Bignall 1990). The geology of the top 305 m of Bore RP1 is described as "recent tephra, alluvium and lacustrine sediments" (Nairn et al. 1994), which is expected to have a low bulk resistivity. Although the Waiotapu and Reporoa Geothermal Fields are proposed to have separate deep geothermal up-flows, shallow geothermal fluids from the WGF are thought to flow into the Reporoa Geothermal Field where mixing occurs (Bignall 1990, Giggenbach et al. 1994, Kaya et al. 2014).

This work will build on understanding the near-surface geological structures and fluid flows (e.g. Giggenbach et al. 1994, Rodriguez-Gomez et al. 2023) in the Waiotapu and Reporoa Geothermal Fields and provide improved insights into how these fields are linked. This paper presents preliminary interpretations of the Waiotapu–Reporoa SkyTEM data in terms of informing geothermal processes and structures key for understanding these systems.

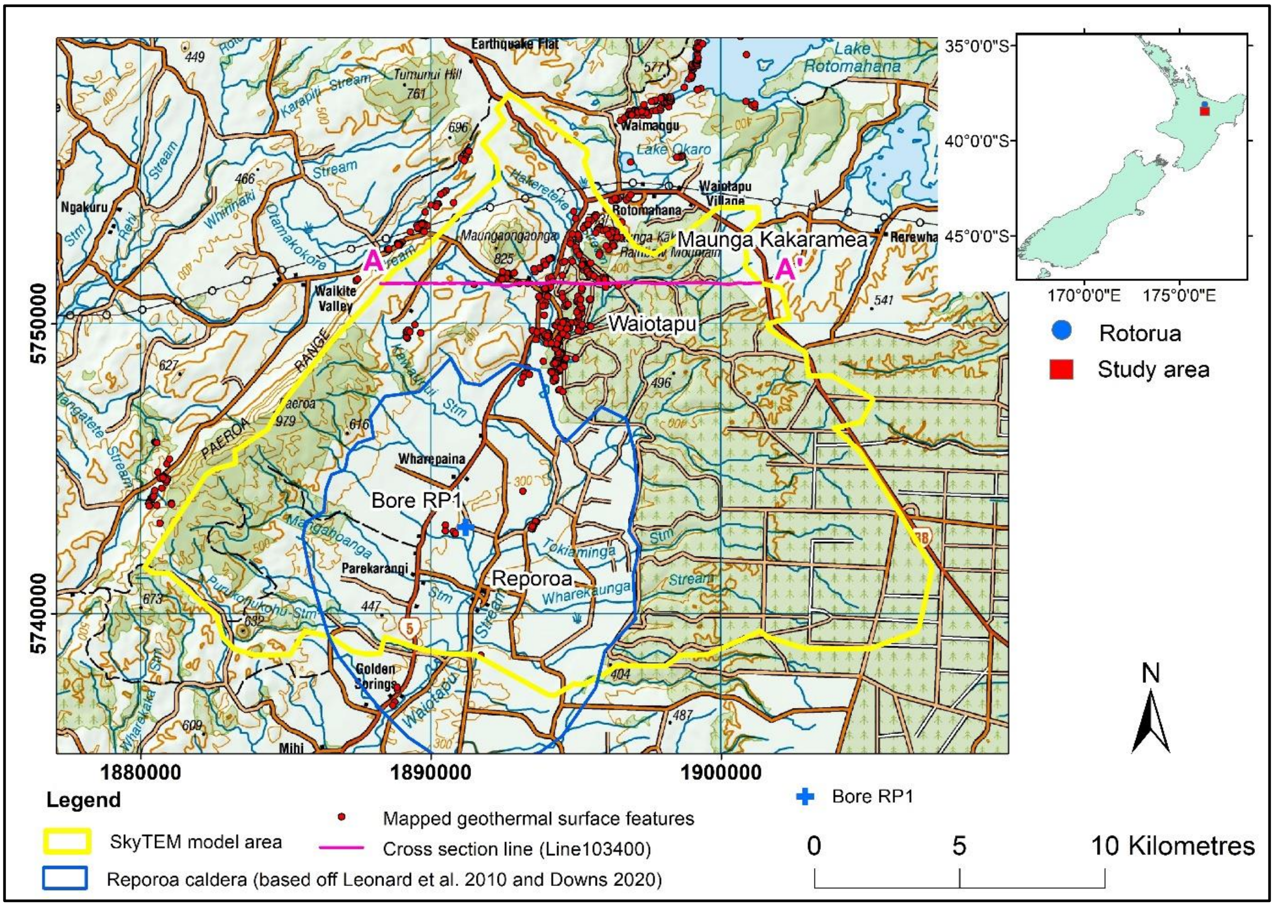

Figure 2: Waiotapu-Reporoa study area. Base map from LINZ (2011).

3. RESULTS AND DISCUSSION

1586 line kilometres of SkyTEM data were acquired over the Waiotapu/Reporoa (Figure 1) area in February 2019 using a SkyTEM304 system operated by SkyTEM Australia Pty Ltd (SkyTEM Australia Pty Ltd 2019). Data were collected approximately every 30 m along 150 W–E-oriented lines, with a line spacing of approximately 200 m. Aarhus University (2019) describes the quality control (e.g. removal of spurious data points, removal of data around electromagnetic sources such as power lines), data processing and 1D resistivity modelling. This paper uses the results of the smooth resistivity model results as-is, with no further discussion on the methods used.

Figure 3 shows a plot of the mean resistivity between 140 and 150 m depth below ground. Key observations from include:

1. Mean resistivities (<20 Ωm) at 140–150 m depth show a generally good correlation to the <30 Ωm contour of the AB/2 = 500 m Direct Current (DC) resistivity map (GNS Science 2022) (Figure 3). The AB/2 = 500 m DC map is used because penetration depths of the SkyTEM survey will be similar to the TEM survey penetration depths that typically range from 100 to 400 m depth. Although patterns between the resistivity map and the TEM resistivity map are similar, SkyTEM resistivities are generally lower than the DC map resistivities. This may be caused by differences in how data are collected and the sensitivity of the methods.
2. There is a good correlation between the locations of geothermal surface features and the low resistivity anomalies (<20 Ωm), suggesting that the low anomalies are caused by shallow geothermal activity (e.g. hydrothermal alteration, saline fluids) but noting that there could be other causes for the low resistivity, such as clays occurring in lacustrine sediments.
3. Higher resistivities (>350 Ωm) correlate well with mapped surface expressions of the rhyolite of Kairuru, rhyolite of Trig 8566 and dacite of Maungaongaonga, Paeroa Formation (in the west) and Kaingaroa Formation (in the east) (Figure 3). The resistivity model enables these deposits to be mapped from the surface to depths greater than 200 m.
4. Steep resistivity gradients are located at the location of some mapped active faults, including the Ngapouri Fault and an unnamed fault (UF1, Figure 3). An extension of the low resistivity zone along the Ngapouri Fault indicates possible geothermal flow at this depth and suggests that part of the Ngapouri Fault provides (or did provide) permeability to geothermal fluids in this area.

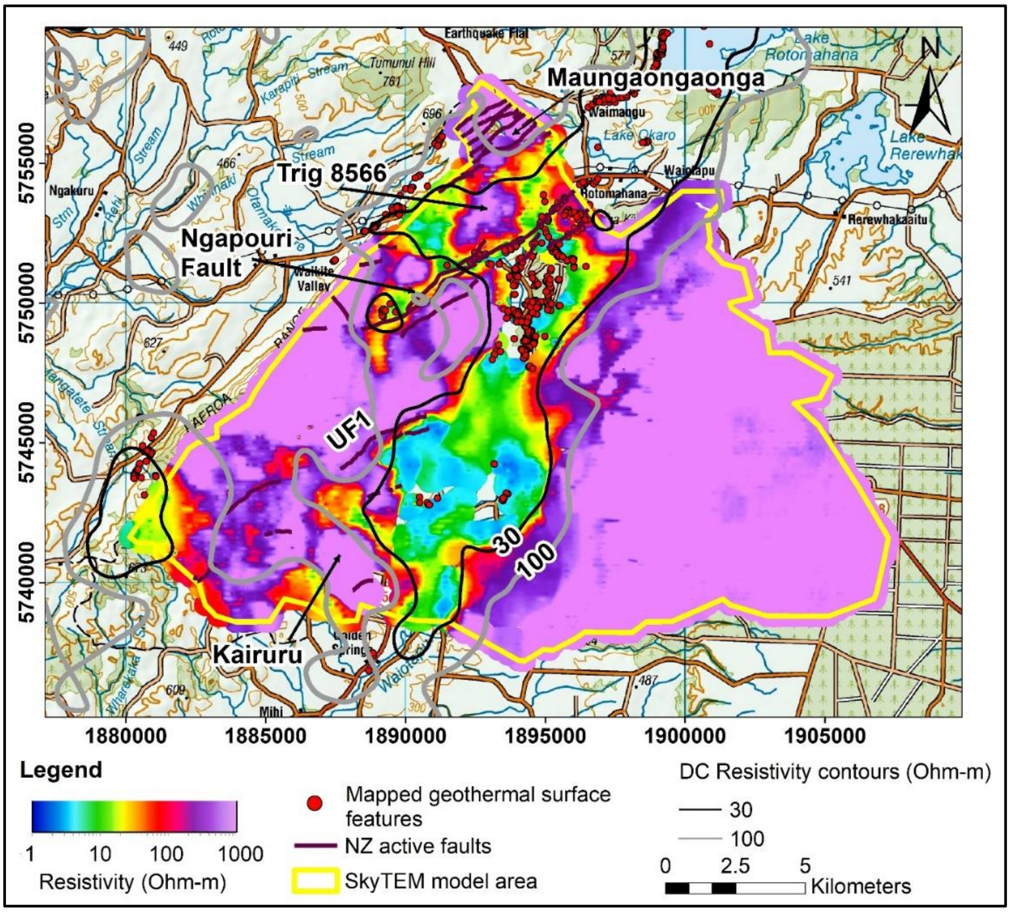

Figure 3: Plot of mean resistivity between 140 and 150 m depth below ground. Note that gaps in the resistivity model indicate areas where the penetration depth of the SkyTEM signal is not suitable to derive a model at this depth. This will generally occur in areas that are very conductive. Only mapped active faults within the SkyTEM model area are shown. Base map from LINZ (2011).

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Figure 4 shows a W–E cross-section along SkyTEM line 103400 (Figure 2). Key observations from Figure 4 show:

1. An abrupt change of resistivity structure at 2970 m (Figure 4) with an approximately 200 m offset of the top of the low resistivity anomaly. The abrupt change coincides with approximate location of the western edge of Lake Ngapouri and the Ngapouri Fault, suggesting a possible structural control on the location of this lake. Lake Ngapouri is a hydrothermal eruption crater that has an inferred age of 680 ± 50 years (Nairn et al. 2005). A thin extension of the low resistivity anomaly to the west at approximately 460 m elevation suggests the presence of an old geothermal liquid outflow. This zone may still be supporting geothermal gas discharges, given that elevated CO_2 mixing ratios measured by Mazot et al. (2014) show elevated mixing ratios at the fault traces and also west of Lake Ngapouri on a survey line located close to the SkyTEM line.

2. An intense low resistivity zone between approximately 3000 and 8400 m close to the ground surface. This corresponds to an area that contains most geothermal surface features along the SkyTEM line, and we would expect at least some of this anomaly to be caused by geothermal influences (clay alteration, and/or hot saline fluids). A drillhole close to the line (Steiner 1963) describes the geology as interbedded siltstones and sandstones for over 100 m, which can also cause a low resistivity anomaly. Very low resistivities also restrict how deep the TEM signals can penetrate, given that highly conductive bodies will absorb the TEM signal, and therefore have a smaller penetration depth for the modelled resistivities. Higher near-surface resistivities between 6000 and 8400 m coincide with different surface geologies in the profile and suggest that these units are capping geothermal fluid flow, or, that vertical permeability is limited through these geological units in this area.

3. A near-vertical resistivity boundary on the eastern side of the Waiotapu Geothermal Field (at approx. 8400 m, Figure 4) could indicate the presence of either a fault or a low permeability geological contact. This may represent an extension of the Kaingaroa Fault, although no fault is mapped at the surface. If so, this appears to bound the geothermal influence in this area. A low resistivity (<5 Ohm-m) zone extends east from the abrupt boundary at approximately 250 m elevation, suggesting geothermal flow into a permeable zone within the Kaingaroa Ignimbrite (?) geological unit if the low resistivity is associated with geothermal influences.

4. Lateral zones of similar resistivities on the eastern side of the cross-section may indicate groundwater aquifers within these units. The higher resistivity sections at approximately 350 m and 250 m elevation may represent aquifers, with the lower resistivity sections representing aquicludes containing more silt and clay. This would require further work to confirm.

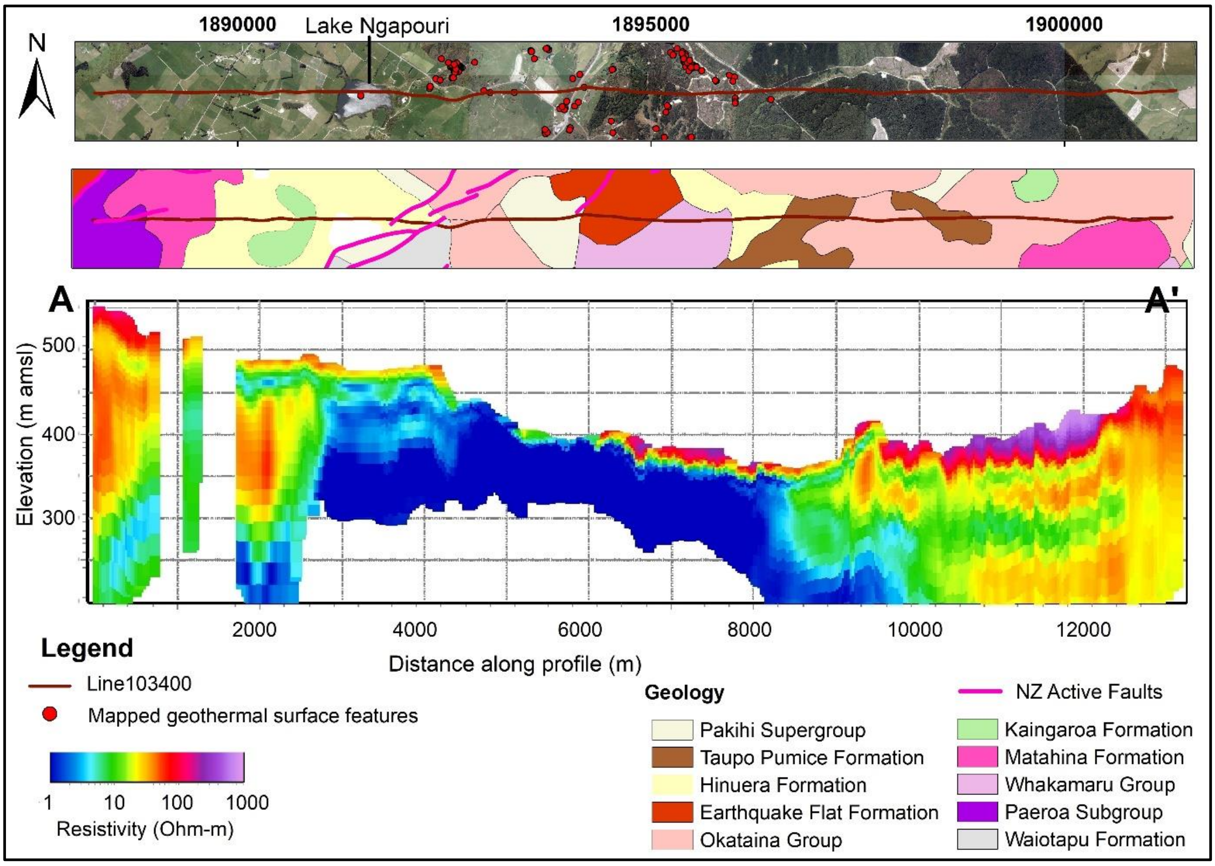

Figure 4: Cross-section A–A' of the SkyTEM resistivity model. See Figure 2 for the location of the cross-section line. Aerial photograph (top section) from LINZ (2014) and geology (middle section) from Leonard et al. (2010), with the cross-section of the resistivity model along line 103400 at the bottom.

4. SUMMARY

Resistivity models derived from SkyTEM data flown over the Waiotapu and Reporoa Geothermal Fields provides new insights into potential near-surface (approx. top 300 m) geothermal fluid pathways. High-density data enable some geological and structural features (e.g. faults) to be clearly defined with depth and interpreted in terms of their influence on geothermal fluid pathways. The pattern of low resistivity anomalies in the area is consistent with other datasets, such as the DC resistivity data, geological data, geothermal surface feature data, CO_2 mixing data and downhole data, thus providing confidence in the results.

Further work, such as drilling and/or borehole nuclear magnetic resonance (to differentiate between permeable and non-permeable conductive layers), would be required to confirm some of the preliminary findings in this paper. This is especially important given that there can be multiple causes of low resistivities in this study area (e.g. geothermal alteration and/or sedimentary deposits).

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