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INTEGRATED APPROACH TO INTERPRETATION OF MAGNETOTELLURIC STUDY AT WAIRAKEI, NEW ZEALAND

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ABSTRACT

Contact Energy Ltd (Contact) undertook a magnetotelluric (MT) survey at the Wairakei-Tauhara geothermal system during early 2010. This study presents MT interpretations for the Wairakei system. Both one-dimensional (1D) and three-dimensional (3D) MT models were developed to maximize confidence in MT data interpretations. While the 3D model is useful to study field wide variations of resistivity, the 1D model allows a more detailed examination of the shallow conductive layers. The availability of drill-hole data and geophysical information (e.g. magnetism) has allowed an integrated interpretation of MT in the context of stratigraphy, structure, hydrothermal alteration and temperature distribution. Some features that stand out in the Wairakei system are the:

1. Correlation between the base of conductive layers as defined by MT, the base of swelling clay zone (as indicated by Methylene Blue tests) and the 200°C isotherm;
2. Lack of conventional, doming shape for conductive layer at upflow area (Te Mihi), possibly due to presence of impermeable rhyolite bodies;
3. Deep outfield (Poihipi West) and infield (Karapiti South) conductors indicating relict alteration, locally in agreement with aeromagnetic anomalies;
4. Deep conductive layer within infield injection area (Otupu)

INTRODUCTION

Electrical DC resistivity surveys proved to be the most effective geophysical tool for identifying the near-surface extent of geothermal systems of the Taupo Volcanic Zone, New Zealand (Risk, 1984; Risk et al., 1999). However, the depth of penetration of this method is generally limited to less than 500 m (Bibby et al., 1998). In order to better understand the deep resistivity structure of the Wairakei geothermal system, Contact undertook an MT survey during early 2010 (Figure 1). The survey extended to the Tauhara area (south-east of Wairakei) including more than 250 MT soundings in total, with nominal spacing of 500 m between MT stations and 14 hr overnight recording time. MT data acquisition and 3D modeling was performed by Geosystem WesternGeco (Geosystem); data quality analysis and 1D-modelling was undertaken by Sinclair Knight Merz (SKM) as part of independent data analysis; and MT interpretations were jointly undertaken by Contact and SKM. Some additional MT measurements were undertaken by GNS-Science in the Karapiti South area (Figure 1) during early 2010 in the context of a separate research programme. Both Geosystem and GNS-Science datasets were combined for 1D and 3D modeling purposes.

MT generally plays a central role in the definition of drilling targets during the early stages of geothermal exploration, with the application of MT heavily relying on conventional conceptual models of resistivity, where upflow structures are traditionally associated with a doming shape of the bottom of the conductive layer. Conducting an MT survey in a developed geothermal field, such as Wairakei-Tauhara, has provided an opportunity to: integrate MT data with drill-hole datasets and other geophysical anomalies (e.g. magnetic), assess the validity of conventional models of resistivity, improve our understanding of the complexities and controls on resistivity in an active high-temperature geothermal field, and explore the implications of a 3D resistivity structure for drill targeting strategies.

DATA ANALYSIS

The depth of penetration of the MT method is a function of signal period and resistivity (e.g., Vozoff, 1978), and therefore, is expected to be highly variable across high-temperature geothermal systems like Wairakei, where conductive layers of different thicknesses and intensities occur. In this context, a reliable depth of 1000 m to 1500 m is regarded conservative for 1D and 3D MT interpretations, respectively. The relatively more limited reliability of 1D models with depth is due to 3D artifacts inherent to 1D modeling. Generally speaking, however, 1D models tend to best highlight shallow resistivity variations, and were therefore, the most useful for well-by-well comparisons of resistivity and drill-hole data (see Appendix 1 for examples). In comparison, the 3D model is more robust but smoother and therefore, better suited to study field wide variations of resistivity.

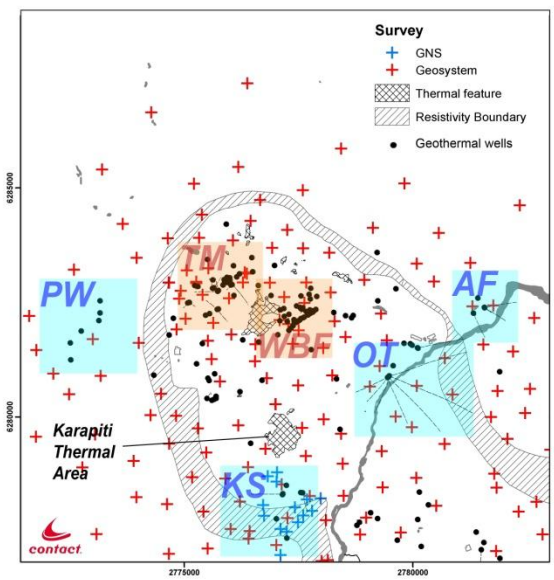

Figure 1: Wairakei MT survey points. TM = Te Mihi (production); PW = Poihipi West (injection); KS = Karapiti South (injection); WBF = Western Bore Field (production); OT = Otupu (injection); AF = Aratiatia Flats (injection – decommissioned)

INTEGRATION WITH DRILL-HOLE DATA

Integration of stratigraphy, clay hydrothermal alteration (from Methylene Blue Titration - MeB) and 1D MT models of resistivity are shown for selected wells in Appendix 1. For illustration purposes, wells have been classified as infield, peripheral or outfield. The following standardizations are introduced:

1. Swelling clay layer is defined by swelling clay > 5% (MeB titration)
2. Top and bottom of conductor layer are interpreted from the 1D model, based on both resistivity values (generally < 5 Ohm-m) and geometry of conductive layers.

Based on the standardizations above, some correlation is observed between the zones of electrically conductive layers and high swelling clay. Using the standardizations above, outfield areas are generally characterized by absent swelling clay zones and conductive layers. X-Ray Diffraction tests were carried out in selected wells (not shown here) and results used to map the transition from illite-smectite to illite. In general, this transition coincides with the base of the swelling clay zone.

An implication of the correlation of MT and MeB is that MT anomalies primarily reflect electrically conductive swelling clay distribution. As discussed by Ussher et al (2000), other factors controlling resistivity include temperature and salinity. The presence of a geothermal brine, although associated with low resistivity, is confined to pore space of the rock matrix and therefore has comparatively less impact on the overall resistivity. Based on Ussher et al (2000), an interesting comparison can be made between *hot* and *cold* swelling clay, with the former potentially able to produce a resistivity anomaly up to one order of magnitude lower than the *cold* counterpart. The terms *hot* and *cold* refer here to active/convective and cold/conductive portions of a geothermal system, respectively.

The conventional models of resistivity for high-temperature geothermal systems predict that the base of the conductive layer occurs at relatively shallow depths in or adjacent to upflow areas. At Wairakei, this holds true partially (e.g. WKM14; Appendix 1), as there are some deep MT anomalies near the postulated upflow of Te Mihi (e.g. WK263; Appendix 1). In some instances, lithological controls can be advocated to explain discontinuities in the observed MeB anomalies, such as in WKM15 (Appendix 1), where Upper and Lower members of Huka Falls Formation seem to concentrate greater swelling clay contents relative to the pumice breccias of Middle Huka Falls Formation (Appendix 1), (geological units described in detail by Bignall et al., 2010).

At Otupu infield injection area, MT models predict a much deeper conductive layer compared to MeB anomalies (e.g. WK317; Appendix 1). Although this discrepancy poses some questions in terms of resolution and sensitivity of the methods, both MT

and MeB show a clear field-wide trend of a deepening conductor. It is worth noting that such a deep conductor is centered on WK301 (e.g. Figure 5), the deepest injection well in the Otupu area, suggesting that this deep conductor may be injection-induced. To test the hypothesis of injection-related resistivity changes, further studies will be undertaken, including measuring the amount of swelling clay in cuttings from early, pre-injection wells.

The resistivity signature of peripheral and outfield wells is variable and interpretation requires understanding of the particular setting of each well. WK404 is located in Karapiti South (Figure 1) and it is affected by a shallow temperature inversion associated with a lateral outflow from Wairakei, whose surface expression is the Karapiti thermal area (Figure 1). This lateral thermal anomaly is reflected in the shallow conductor detected by MeB and MT (Appendix 1). WK402 is located further south near the outer resistivity boundary in an area where the conductive layer (as defined by MT) is absent. In agreement with this, drilling results show low (outfield) temperatures and relative absence of swelling clay (Appendix 1).

WK315 is located in the Aratiatia Flats area (Figure 1) and exemplifies the resistivity signature of an outfield region thermally and hydrologically disconnected from the main reservoir. In this instance, MT shows sharp resistivity variations from infield to outfield areas (Figure 2 and Figure 3), and drilling findings included no swelling clay anomalies (as indicated by MeB) and a thermal regime being dominantly cold-conductive. The injection capacity of the Aratiatia Flats region (Figure 1) proved very limited and after injection trials starting in 2009, injection was decommissioned in 2010. Other outfield areas at Wairakei, like Poihipi West (Figure 1), are similarly dominated by a cold-conductive thermal regime but unlike in the Aratiatia Flats area (WK315; Figure 1), anomalous amounts of swelling clay were found in WK681 (Appendix 1). This swelling clay is interpreted as relict and the transitional (and relict) variations of resistivity from infield to outfield areas anticipated by the 3D MT model in the Poihipi West area (Figure 2 and Figure 3) indicate past connectivity between outfield and infield regions. Whether or not such connectivity remains an active condition and whether it will have a positive impact on injection performance of the Poihipi West area is being currently assessed during injection trials.

FIELD-WIDE DATA ANALYSIS

Figures 2, 3, 4 and 5 show maps of resistivity from the 3D MT model at nominal depths of 50-200 m, 200-350 m, 450-600 m and 850-1000 m, respectively. The best correlation between <5 Ohm-m anomalies and the conventional resistivity boundary (Schlumberger survey, 1000 m spacing) is obtained at a depth of less than 200 m (Figure 2), suggesting the known resistivity boundary (Risk, 1984) provides a relatively shallow, 2D picture of resistivity. More interestingly, this depth of penetration is much shallower than the nominal depth of penetration of 600 m postulated for DC resistivity surveys with AB/2 = 1000 m (Bibby et al., 1995). Based on Figures 2-5, other features out of note in the Wairakei system include:

1. Good correlation of thermal features and shallow resistivity lows (Figure 2 and 6).
2. Lack of conventional “resistivity low” within interpreted upflow area (Te Mihi). In contrast, resistivity lows occur south of the main production areas (Figures 3, 4 and 5).
3. Deep outfield and infield conductors indicating relict alteration (Figures 3, 4 and 5). This is confirmed by recent drilling results at Poihipi West.
4. Deep conductive layer within injection area at Wairakei (Figure 4).

In order to address point 2 above, Appendix 2 shows two cross sections of resistivity based on 3D MT models (see Figure 3 for location of cross sections in map view), integrated with interpreted reservoir temperatures and stratigraphy. The expected correlation between the base of the conductive-swelling clay layer and the 180-200°C isotherms is clear in the Te Mihi area (postulated upflow) but a mismatch is observed to the southeast, where the base of the conductive layers tends to follow the top of the Karapiti 2A rhyolite rather than the 200°C isotherm. Independent reservoir engineering data from the Wairakei field (e.g. temperature distribution, feed zones) point to relatively high permeability in the margins of many rhyolite bodies and relatively low permeability within their cores. Accordingly, the geometry of the conductive layer south of Te Mihi is interpreted as reflective of permeability distribution rather than temperature distribution (core of Karapiti 2A rhyolite relatively impermeable and less altered).

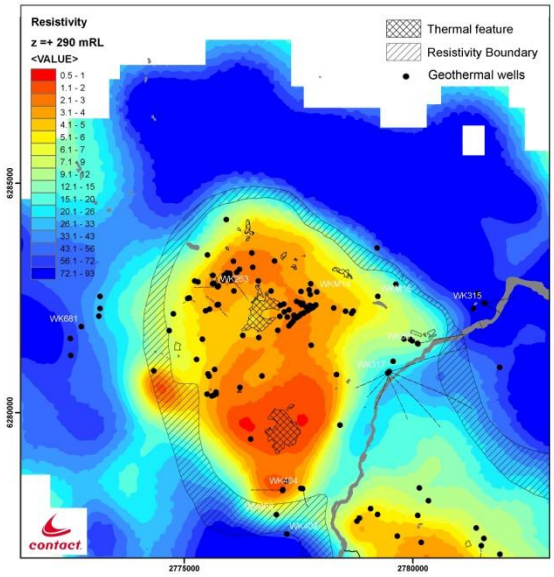

Figure 2: Resistivity map of Wairakei, at z = +290 mRL based on 3D MT model (equivalent depth range 50-200 mGL approx.).

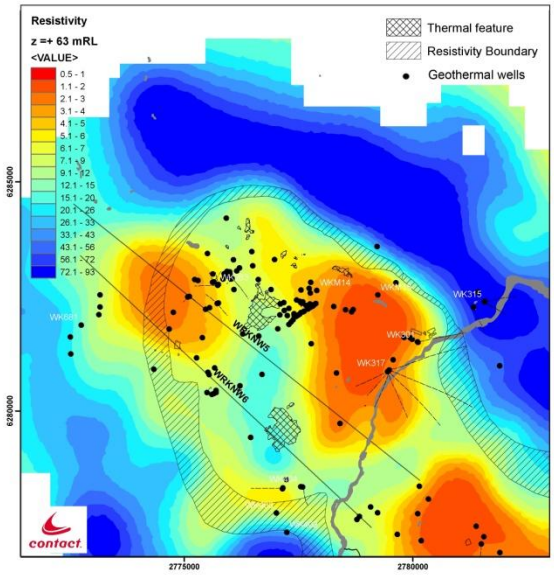

Figure 3: Resistivity map of Wairakei, at z = +63 mRL based on 3D MT model (equivalent depth range 300-450 mGL approx). Strike of cross sections in Appendix shown for reference.

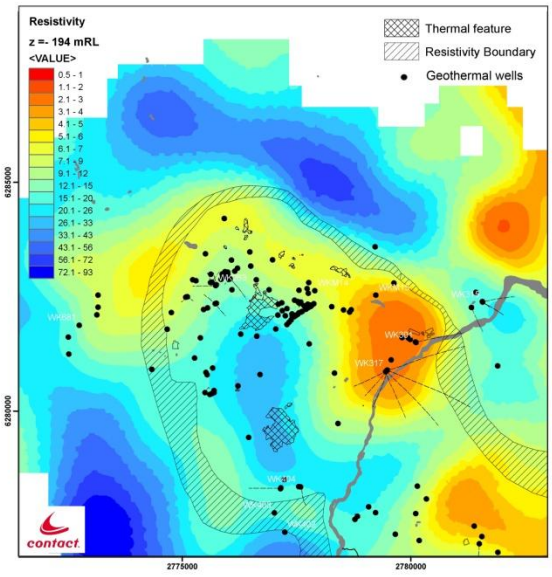

Figure 4: Resistivity map of Wairakei, at z = -194 mRL based on 3D MT model (equivalent depth range 550-700 mGL approx).

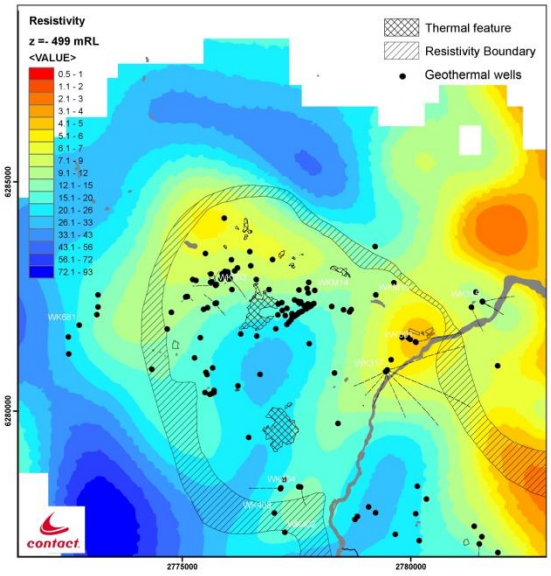

Figure 5: Resistivity map of Wairakei, at z = -499 mRL based on 3D MT model (equivalent depth range 850-1000 mGL approx).

JOINT INTERPRETATION: AEROMAGNETICS

Figure 6 shows a reduced-to-pole (RTP) magnetic anomaly map for the Wairakei field, highlighting an interpreted boundary of low magnetic intensity. This low magnetic intensity region is primarily interpreted in terms of hydrothermally-induced rock demagnetization. Figure 7 shows the interpreted hydrothermal demagnetisation boundary against MT data at z = +63 mRL. Other potential sources of low magnetization include reversely magnetized rocks, which generally correspond to volcanic rocks older than 0.73 Ma (last magnetic reversal). The Wairakei Ignimbrite (Appendix 1; Bignall et al., 2010) is a stratigraphic marker at Wairakei which correlates with the ca. 0.33 Ma old Whakamaru Ignimbrite Group (Wilson et al., 1986). At Wairakei, the base of the Wairakei Ignimbrite is known to be generally deeper than 1500 m, indicating that volcanic rocks older than 0.73 Ma are also likely to be much deeper than 1500 m. Deep anomalous sources tend to have less effect on the observed surface magnetic anomalies suggesting that deep, reversely magnetized rocks have a secondary role on the interpretation of observed magnetic anomalies at Wairakei.

Bearing in mind the uncertainty in depth of penetration of magnetic data, the following observations can be made:

1. Both MT and aeromagnetics show hydrothermal alteration extending beyond the resistivity boundary in the Poihipi West area and west of the Karapiti Thermal area. Drill-hole data (WK681) confirms this corresponds to relict alteration in an outfield setting.
2. A relatively high magnetic intensity region occurs south of Wairakei extending to the outfield areas, which can be spatially correlated with the Karapiti 2A rhyolite. This provides an independent indication of a relatively unaltered, potentially highly magnetic intensity unit, in consistency with inferences from MT of a relatively impermeable unit south of Wairakei (Appendix 2).
3. Good agreement between low magnetic intensity regions and postulated upflow (Te Mihi), as well as good correlation of local low magnetic intensity anomalies with thermal features (e.g. Karapiti thermal area). These features (upflow area and Karapiti thermal area) are not highlighted in detail by MT.

It is also interesting to note that there are some areas of high discrepancy between MT and aeromagnetics. In particular, the north-eastern boundary of Wairakei is a relatively sharp resistivity boundary as demonstrated by MT (Figure 7). Drilling data confirms that reservoir conditions are quite contrasting either side of the boundary, with the outfield region being unaltered and dominated by a cold conductive thermal regime. Such northeastern boundary is highlighted only locally by aeromagnetics.

Another point of interest is the deep, thick and strong conductor at the injection area of Wairakei indicated by MT data, which is only associated with a slight aeromagnetic low (Figure 6). It is worth noting magnetic data was collected during early 90's, and large scale injection commenced during mid 90's. Injection-related effects on resistivity, particularly, development of clay alteration in response to injection of brine offers a possible explanation for the different features highlighted by MT and magnetic anomalies.

The analysis above highlights the importance of integrated analysis of geophysical and drill-hole datasets in order to recognize and understand the implications for reservoir structure and evolution.

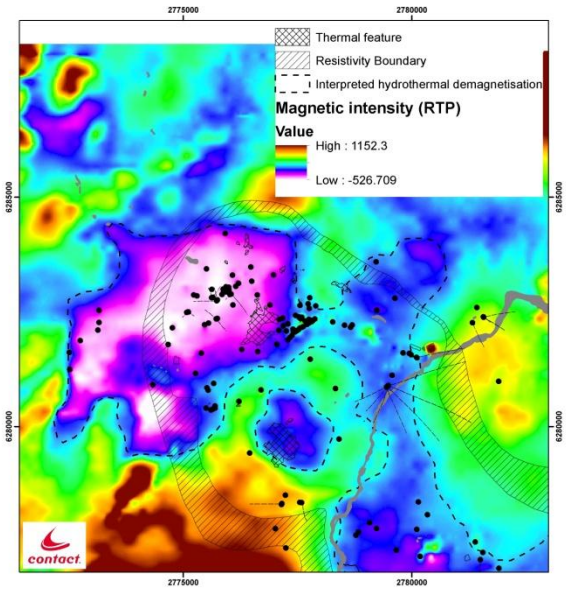

Figure 6: Reduced-to-pole magnetic intensity anomaly map of Wairakei.

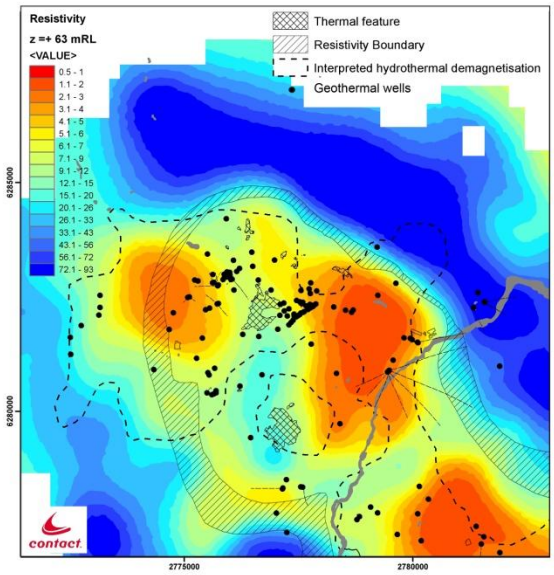

Figure 7: Boundary of hydrothermal demagnetization interpreted from magnetic anomalies superimposed on resistivity map at z = +63 mRL.

FINAL REMARKS

The 3D resistivity signature of Wairakei, as imaged by a recent MT survey, demonstrates the complexities of resistivity distribution in high-temperature geothermal systems. The availability of drill-hole data and other geophysical datasets has been used to assist the interpretation of MT results and shows that MT primarily characterises clay alteration distribution, with temperature and permeability being important controlling factors. In developed fields, the MT interpretations must consider the dynamic nature of geothermal systems, the potential effects of relict alteration and potentially production-induced processes (e.g. injection).

ACKNOWLEDGMENTS

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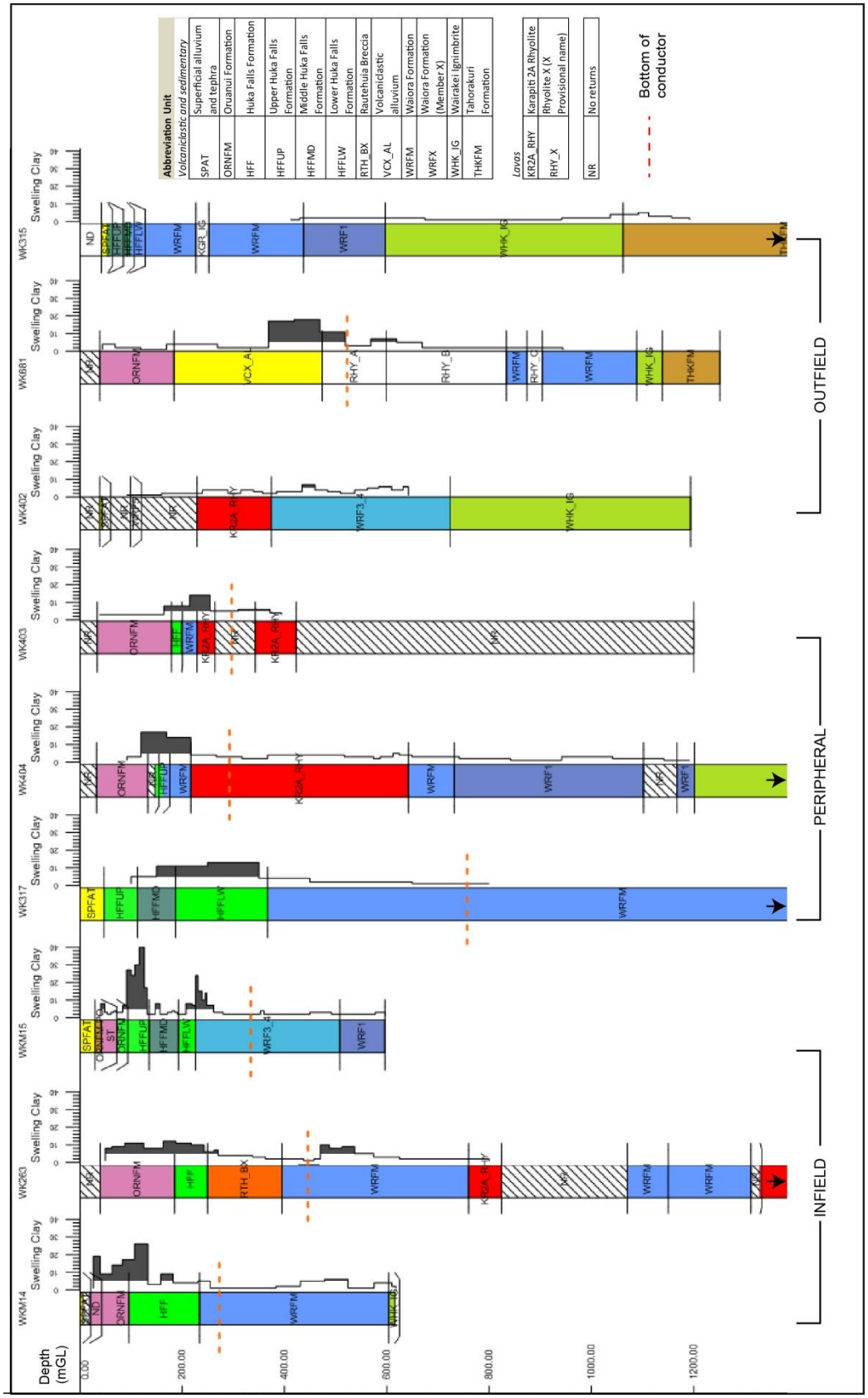
APPENDIX 1 – Bottom of conductive layer from MT (1D model) and selected drill-hole data



APPENDIX 2 – Cross sections of MT, interpreted stratigraphy and temperature