

Wairakei Geothermal Field Boundary: Insights from Recent Geophysics and Reservoir Information

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ABSTRACT

Resistivity from conventional DC surveys has been historically regarded a useful indicator of the Wairakei field boundary. It is also accepted that the penetration of DC resistivity methods is limited to shallow (< 500 m) depths. In order to address limitations in the depth of penetration, we present an up-to-date review of geoscientific and reservoir data with emphasis on the delineation of the field boundary at depths greater than 500 m. Based on interpretation of well pressures (P) and temperatures (T), we classified selected wells into infield, peripheral and outfield. Field wide extrapolation of the PT boundaries is carried out with the aid of recently (post-2009) acquired geophysics, namely magnetotellurics and microseismicity. At depths greater than 3 km, the modern field boundary is mainly constrained by microseismicity. Three-dimensional complexities of the field boundaries are evidenced through our analysis.

1. INTRODUCTION

The Wairakei-Tauhara geothermal system, New Zealand, is located in the Taupo Volcanic Zone (TVZ), a continental rift system active for the last 2.4 Ma and characterized by one of the world's largest outputs of silicic volcanism and geothermal heat (Bibby et al., 1995; Wilson et al., 2010). Extension over the TVZ rift has manifested through the development of NE-SW trending normal faults (e.g. Rowland and Sibson, 2004), herein referred to as the "TVZ trend".

The Wairakei geothermal field has been in commercial operation since 1958 with a current installed capacity of 375 MWe (largest installed capacity and longest operating history any New Zealand geothermal field). The Wairakei geothermal system is part of the greater Wairakei-Tauhara geothermal system (Figure 1), with the Tauhara geothermal field also under development and supplying steam into the Te Huka Power Station (23 MWe; Figure 1) and into direct use applications. Over the productive lifetime of the Wairakei geothermal field, a number of geophysical investigations have been carried out, a summary of which is given by Hunt et al. (2009). Of these, resistivity anomalies mapped through conventional DC surveys (e.g., Risk, 1984) are among the most relevant due to good agreement between low resistivity and areas of hot geothermal resource. However, DC resistivity is known to: 1) have a limited depth of penetration (< 500 m nominal depth); 2) provide poor insight into the underlying three-dimensional resistivity structure; 3) be strongly sensitive to hydrothermal clay alteration, which can be potentially relict. Aware of the potential limitations of resistivity, Bixley (1994) had already pointed out the relevance of looking into a multidisciplinary approach for the interpretation of field boundaries in developed geothermal systems of New Zealand. In this context, the post-2009 period has seen a resurgence of geophysical investigations at Wairakei, lead by magnetotellurics (MT) and high-resolution microseismicity (Sepulveda et al., 2012; 2013). In addition, drilling completed during the period 2005-2013 at Wairakei helped consolidate an expansion of production and injection as part of the development of Te Mihi Power Station, to be commissioned during early 2014 (Figure 1). Cumulative geoscientific and reservoir data gathered to date provides an opportunity for an integrated and multidisciplinary interpretation of the geothermal system boundaries. For simplicity, we present two indicative boundaries representative of the shallow (500-3000 m depth) reservoir and deep (> 3000 m depth) geothermal system.

2. GEOTHERMAL SYSTEM BOUNDARIES

2.1 Magnetotellurics

With the advent of MT studies, a three-dimensional (3-D) picture of resistivity has become available at Wairakei. We define the "shallow MT conductor" as the 3-D region of low resistivity (≤ 5 Ohm-m) down to 700 m depth as determined from MT surveys. An outline of this MT conductor (Figure 2) shows a relatively good correspondence with the resistivity boundary determined from DC resistivity traversing. In terms of lateral extent of the MT conductor, there are nevertheless some discrepancies in the MT-based resistivity structure with respect to the resistivity boundary, such as: 1) NE-SW elongate discontinuity of the MT conductor on the transition between Wairakei and Tauhara. This discontinuity is interrupted locally near the southern margin (Karapiti area – see Figure 1) where the MT conductor continuously straddles across the two fields; 2) Extent of MT conductor beyond the resistivity boundary near the western margin of the field; 3) minor discontinuity in the MT conductor south of Te Mihi and west of the WBF (Figure 1).

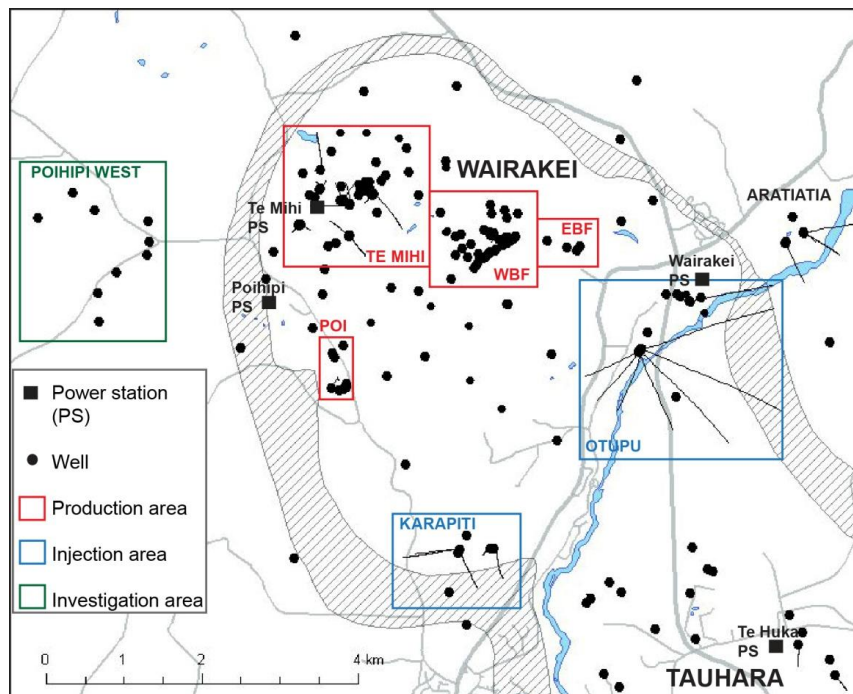


Figure 1. Map of production and injection areas of the Wairakei field shown relative to the resistivity boundary (hatched area). Tauhara geothermal field to the south-east. Key: EBF = Eastern Borefield; WBF = Western Borefield; POI = Poihipi.

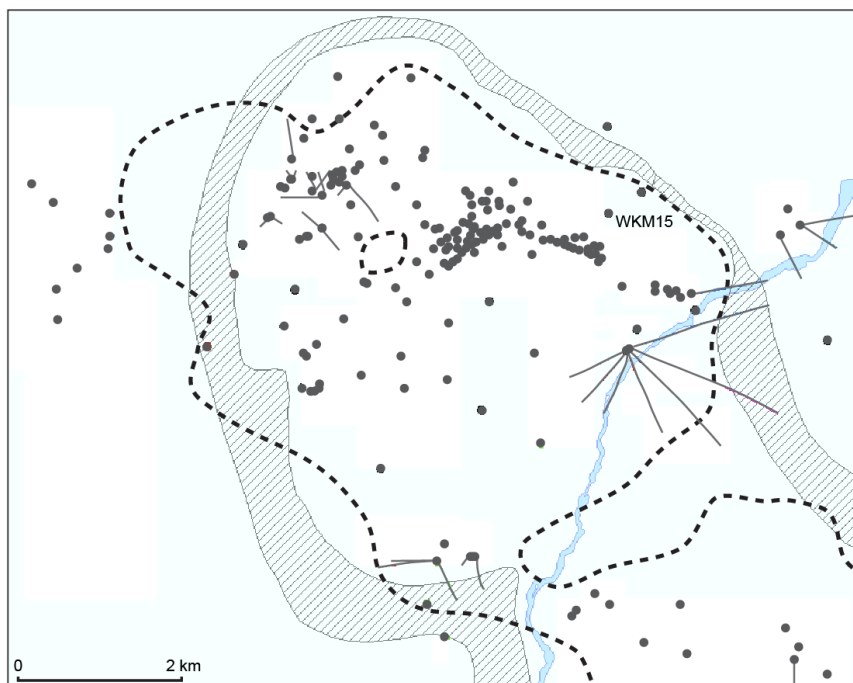


Figure 2: Map of the Wairakei Field showing wells, conventional resistivity boundary and the outline of the shallow MT conductor down to 700 m depth (dashed line) based on a 3-D model of resistivity

In order to better understand the lateral and vertical extent of the MT conductor, a review of MT interpretations is presented here. Factors leading to variable extent to low resistivity anomalies include high temperature, high salinity, high rock-matrix clay content and high porosity (e.g. Ussher et al., 2000). Accepting that salinity and temperature are mainly associated with fluids occupying pore space, Ussher et al. (2000) hypothesized that the effect of rock-matrix clay content can be orders of magnitude more dominant than that of fluids. In detail, clay alteration responsible for MT anomalies includes electrically-conductive smectite and interstratified illite-smectite (herein referred to as *swelling clay* for simplicity), which collectively tend to be stable at temperatures lower than $\sim 200^{\circ}\text{C}$ (e.g. Gunderson et al., 2000; Ussher et al., 2000). An interpretation of low resistivity anomalies in terms of swelling clay alteration, herein referred to as “clay-centered” interpretation, has two inherent implications: presence of swelling clay and temperatures $< 200^{\circ}\text{C}$. In terms of vertical extent of the MT conductor, Sepulveda et al. (2012) showed that the base of the MT conductor is controlled to large extent by the $\sim 210^{\circ}\text{C}$ isotherm and its correlation with clay alteration was verified in a number of locations where clay alteration data were available, supporting a clay-centered interpretation of MT anomalies.

Based on the natural decrease of temperature towards the reservoir boundaries, an increased stability of swelling clays can be predicted. Accordingly, it is not the instability of clays that explain the lateral disappearance of the MT conductor towards the margins of the geothermal system. Some authors have proposed that a clay-rich, MT conductor acts like a shallow cap or seal at the top and sides of high-temperature reservoirs (e.g. Gunderson et al., 2000) explaining the lack of clay alteration in outfield regions. However, this can be a circular argument because permeability is a pre-requisite for hydrothermal alteration to occur. A connection between low resistivity and clay-rich, relatively impermeable formations was similarly implied at Wairakei during early DC resistivity investigations (Risk, 1984). Huka Falls Formation (HFF) is a relatively shallow and continuous formation throughout Wairakei, thought to serve as a shallow cap of the productive reservoir. From top to bottom, HFF unit comprises three members, namely, Upper, Middle and Lower, with Upper and Lower members made up of relatively impermeable lacustrine sediments and Middle HFF member corresponding to a relatively permeable volcanic breccia (see Bignall et al., 2010 for detailed review of geology). High peaks of swelling clay within Upper and Lower HFF units observed locally (e.g. well WKM15; Figure 2; Sepulveda et al., 2012) support Risk (1984)'s view of lithologically-controlled hydrothermal clay content associated with clay-rich formations. Examined in detail, PT data and geological evidence from well WKM15 (continuously cored) and nearby favors the existence of outflows channeled through Middle HFF and the interface of Lower HFF and Waiora Formation, with maximum temperatures of ~130°C and ~170°C, respectively. Maximum cooling of ~80°C (from ~220°C down to ~140°C) documented for the period 1955-1975 in neighboring wells (e.g. Bixley et al., 2009) suggests that both Middle HFF and Lower HFF-Waiora Formation aquifers could have had pre-production temperatures in excess of 200°C (where swelling clay is unstable). In agreement with a clay-centered interpretation, the presence of swelling clay within Upper and Lower HFF and the relative lack of swelling clay within Middle HFF and under HFF could be a combined effect of pre-production temperatures and lithology. On a field wide scale, the vertical extent of the MT conductor to depths greater than that of HFF confirms that MT anomalies are not necessarily confined to swelling clay-rich, HFF-type formations. In terms of lateral extension, HFF is known to be absent locally at Poihipi West (see Figure 1) and thinning out locally south of Te Mihi and north of Karapiti (see Figure 1).

An example of the MT conductor not vertically confined to clay-rich, HFF-type formations is found at Otupu (See Figure 1). Large-scale injection has been undertaken in this area since the mid 90's. Pre-injection, low resistivity anomalies were identified during early DC resistivity surveys (Risk et al. 1984) but post-injection MT surveys (carried out in 2010) revealed an unusual thickness and depth of the MT conductor reaching the base of Waiora Formation at ~800 m depth (Sepulveda et al., 2012). MT findings prompted a study of swelling clay alteration looking into correlations of MT and clay alteration and possible injection-related effects on clay alteration. Results of this study (Correa et al., 2013) showed a poor correlation between the MT conductor and swelling clay (the latter being thin and superficial), and no conclusive evidence for effects of injection on clay alteration. Correa et al. (2013) attributed the thick MT conductor to lateral outflows within Waiora Formation. We refer to this interpretation of the MT conductor as "fluid-centered". The implications of a fluid-centered interpretation are threefold: high temperature, high salinity and high porosity. Well temperature data at Otupu support the presence of pre-injection shallow (<700 m depth) lateral outflows of geothermal fluids with temperatures in the typical range of 100-200°C. Until 2006, the typical injection fluid at Otupu was ~130°C and 1800 ppm Cl (for reference, deep reservoir fluid estimated at <1650 ppm Cl; Brown et al., 1988). Further modeling work is required to quantify the impact of changes of salinity and temperature on resistivity but the relatively small contrast between end-member compositions suggests minor changes on resistivity.

In the area south of Te Mihi (and north of Karapiti), Sepulveda et al. (2012) showed that the base of the MT conductor did not match temperatures but rather mimicked the rim of a 500 m thick rhyolite, suggesting that the rhyolite core served as an impermeable barrier to hydrothermal alteration. In the western margin of the field (Poihipi West area; see Figure 1), drilling evidence supports the existence of modern cold conditions (e.g. 50°C at ~1000 m depth) with localized relict swelling clay alteration at depths between ~300-600 m and no clay-rich, HFF-type formations. The wide MT conductor reaching beyond the resistivity boundary in this area may be reflecting the effect of relict alteration in the vicinity of Poihipi West (Sepulveda et al., 2012). The potential migration of the field boundary from Poihipi West to its current location (based on DC resistivity) suggests that the western margin might be a transitional one, in contrast to the sharp boundary inferred near the northeast margin (Aratitia area; see Figure 1) where relict clay alteration is absent.

Based on Wairakei evidence summarized in this section, we propose that the shallow MT conductor remains a primary indicator of permeability. The inference of permeability is supported by: 1) where a clay-centered interpretation of the MT conductor is the most feasible, clay is mostly a product of hydrothermal alteration where permeability is a prerequisite; we acknowledge that a fraction of hydrothermal clay can be enhanced by clay-rich formations; 2) where a fluid-centered interpretation of the MT conductor is the most feasible, temperature and salinity can only have a measurable effect on resistivity subject to permeable formations allowing geothermal fluid circulation.

2.2. Microseismicity

Regional seismicity of the TVZ occurs in association with active rifting to depths of ~7-8 km; this seismicity is generally referred to as tectonic seismicity (e.g., Bryan et al., 1999). In detail, however, some clusters of seismicity are found around some geothermal fields (either developed or natural-state), supporting the category of "geothermal" seismicity (Figure 3). The origin and nature of geothermal seismicity (i.e. confined to geothermal systems) is not fully understood, partly because it is not a commonality among all geothermal systems. While Wairakei could be regarded seismically active based on pre-2011 regional seismic records (Figure 3), other geothermal fields have been found to be virtually aseismic (e.g. Ohaaki; Figure 3). For the purposes of this study, we assume that geothermal seismicity falls into two categories: "geothermal-natural", associated with upflowing magma or geothermal fluids, and; "geothermal-induced", associated with fluid injection or fluid extraction. In practice, because geothermal-natural, geothermal-induced and regional-tectonic seismicity can coexist to various degrees, interpreting microseismicity in terms of the boundaries of the geothermal system can be only made as part of a multidisciplinary geoscientific and reservoir analysis.

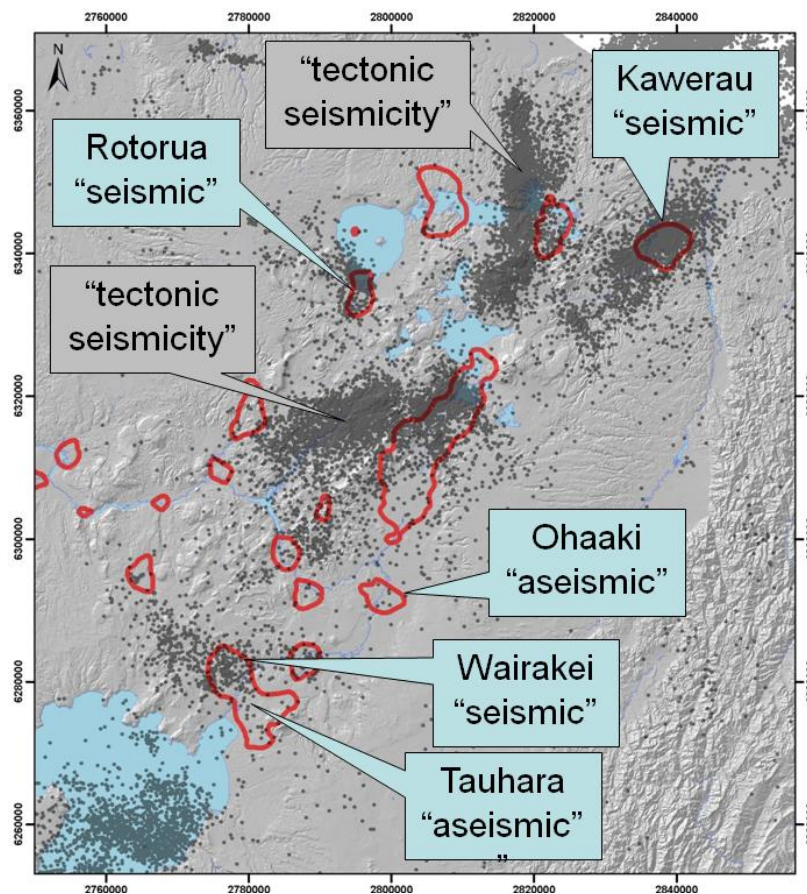


Figure 3: Regional seismicity of the TVZ recorded between 1987-2011 at depths < 5km (black dots, Source GeoNET). Outline of geothermal systems (red lines) based on regional DC resistivity (Stagpoole and Bibby, 1998). Other filtering criteria for seismicity as in Bryan et al. (1999). Map coordinates New Zealand Map Grid System (grid at 20 km spacing).

The known seismic character of the Wairakei geothermal system triggered the commissioning of the Wairakei Seismic Network during early 2009 (Sepulveda et al., 2013). Due to the high resolution and high sensitivity of the seismic network, data collected to date has illuminated new and unprecedented details on the deep thermal and permeability structure of the geothermal system. In terms of vertical distribution of seismicity, 95% and 99% of detected microseismicity occurs above 6.5 and 8.5 km depth, respectively, setting the lower boundary of the geothermal system somewhere in the 6.5-8.5 km depth range (Sepulveda et al., 2013). In this study, maps of continuous seismic energy (see Sepulveda et al., 2013 for methodology) obtained at different depths are used as representations of the shallow (< 3 km) and deep (> 3km) microseismicity (Figure 4). While shallow microseismicity tends to be confined to within the resistivity boundary, a significant portion of deep microseismicity falls outside of the resistivity boundary near the NW margin of the field.

Shallow microseismicity is not continuous throughout the region within the resistivity boundary. A subtle but persistent seismic gap indeed separates microseismicity near Otupū from the bulk of the microseismicity in the field. In the lack of high-resolution, pre-injection seismic records at Otupū (injection area since mid 90's), the spatial correlation of Otupū microseismicity with injection wells and the existence of the seismic discontinuity referred to above, are used to infer a larger component of induced microseismicity at Otupū relative to the bulk of shallow microseismicity in the field. Microseismicity near Karapiti (particularly north and east of Karapiti; Figure 4a) cannot be differentiated from the bulk of microseismicity on a spatial basis but the availability of pre-injection seismic records (Karapiti injection commissioned August 2012) and post-injection increase in activity also supports a component of induced microseismicity near Karapiti. Moving north from Otupū and Karapiti, microseismicity is assumed to be mostly geothermal-natural in origin although we speculate that the fluid withdrawal-induced pressure changes in the productive reservoir, further discussed in section 2.3, could have also theoretically resulted in a component of induced microseismicity in the production areas. Further studies are required to assess this possibility.

Regarding deep microseismicity (Figure 4b), establishing the proportions of geothermal-natural and regional-tectonic seismicity is of key relevance to the definition of the deep geothermal system boundaries. The strong NE-SW striking direction of the deep seismic anomalies (Figure 4b) is in agreement with the TVZ trend which might suggest a tectonic origin. However, a tectonic origin does not satisfactorily explain why deep microseismicity is strongly clustered around the immediate vicinity of the Wairakei geothermal system. Instead, this spatial correlation promotes a genetic linkage to the geothermal system. Also, the proved ability of the Wairakei Seismic Network to detect remote, low magnitude seismic events (~10 km distance nominal), and a comparison with the New Zealand wide GeoNet seismic network (Figure 3), suggests the decrease of microseismicity to the NE and SW of the deep microseismicity outline in Figure 4b is real and not an artifact of network detection limits. In the lights of Rowland et al. (2010) who have suggested that rifting of the TVZ is not necessarily purely tectonic but can be also a magma-assisted process, and in the light of the strong NE-SW trend of deep microseismicity at Wairakei, we hypothesize that (deep) geothermal microseismicity is not necessarily a separate category of tectonic microseismicity but rather a sub-category where rifting is enhanced by the

presence of magmatic and/or geothermal fluids. The study of temporal occurrence of deep microseismicity and cluster analysis (beyond the scope of this paper) is expected to further our understanding of tectonic versus geothermal microseismicity.

The strong shift of microseismicity with respect to the shallow resistivity boundary suggests that the deep upflow of the Wairakei geothermal field is offset with respect to the shallow DC boundary. This possibility might not be an isolated example of the TVZ. As a matter of fact, a pattern of deeper (3-7 km), subvertical, low resistivity anomalies underlying high-temperature geothermal systems has recently emerged following MT investigations in the TVZ (Bertrand et al., 2012). These authors have shown that for some geothermal systems (Wairakei not included in this study) deep MT conductors can be offset from the shallow field boundaries and speculated on this basis that deep geothermal upflows can be situated in outfield locations.

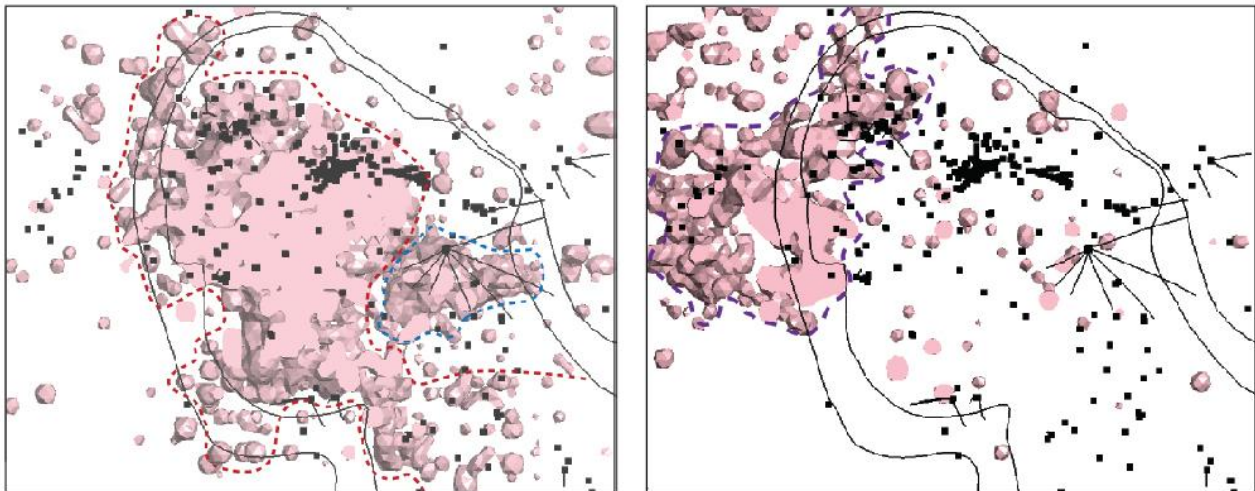


Figure 4: 3-D solid models of seismic energy based on microseismicity collected between March 2009 and June 2013. Regions of high seismic energy indicated by dashed lines. A) Shallow microseismicity (~1.2-2.7 km depth). Otupu microseismicity (blue dashed line) is differentiated from the bulk of microseismicity (red dashed line); B) Deep microseismicity (~5.5-7 km depth)

2.3 Reservoir boundary

Temperature is generally considered the primary indicator of the boundaries of a geothermal system. In this study, however, we approach the definition of a reservoir boundary with focus on pressure drawdown in response to production. This approach might not be suitable at all geothermal systems, and particularly “green fields” where reservoir pressures are undisturbed. At Wairakei, however, a pressure decline of up to 25 bars associated with fluid extraction has been documented (Bixley et al., 2009) which propagated throughout the reservoir. In the neighboring Tauhara field, pressures have also declined in response to production at Wairakei and closely followed the Wairakei trends since they were first measured in 1964. The bulk of the pressure drop at Wairakei took place shortly after production and by the mid 70’s pressures had stabilized. Since 1998 pressures throughout the Wairakei reservoir have been slowly increasing as a result of injection (Otupu area; see Figure 1), with a total pressure increase to date of about 5 bars. A more recent diversification of injection in the south part of the field (since August 2012; Karapiti area – see Figure 1) has provided new insights into pressure regimes across Wairakei-Tauhara. Milloy and Wei Lim (2012) showed that pressures in the relatively recent Karapiti wells lay on the Tauhara pressure trend rather than on the Wairakei pressure trend (Figure 4), suggesting that the Karapiti area corresponds to the northern extension of Tauhara, rather than the southern extension of Wairakei.

Modern reservoir pressures from a range of production, injection and monitoring wells are shown in Figure 5. These pressures are taken from the period 2008-2013 when pressures were relatively stable across the Tauhara and Wairakei reservoirs. Based on relative differences, wells are grouped into infield, peripheral and outfield categories. However, a continuous spectrum of pressures can be observed associated with both vertical and lateral variations in pressure regimes. In order to capture this variability, categories also make reference to geographic locations where relevant. A map view of pressure data in Figure 5 is shown in Figure 6, together with an interpreted reservoir boundary, which takes into account pressure-based categories, microseismicity and MT anomalies. In this definition, favorable indicators of a geothermal system include presence of the shallow MT conductor, presence of microseismicity and infield pressure regimes. For highly directional wells, pressure data is indicated at the point along well track corresponding to the major feed zone of the well.

Well temperatures are qualitatively examined here. Wells located in the outfield locations (relative to the interpreted reservoir boundary in Figure 6) have a common pattern of a dominantly linear increase of temperature with depth. Maximum temperatures of outfield wells are plotted with depth in Figure 7. This analysis suggests that the areas of Poihipi West and Aratiatia actually fall on slightly different conductive temperature regimes. Another interesting observation from Figure 7 is that the gap between infield and outfield temperatures potentially narrows down with depth, highlighting the potential risks associated with defining a reservoir boundary on the basis of absolute temperatures only.

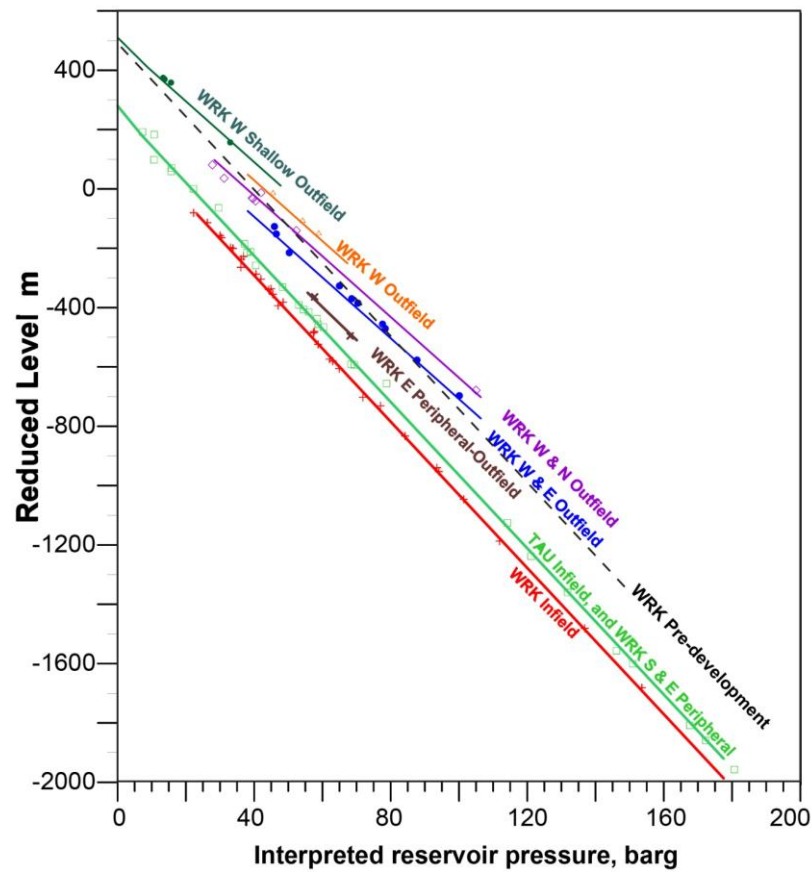


Figure 5. Pressure regimes for different wells at Wairakei and pressure-based categorization compared to interpreted pre-development pressures

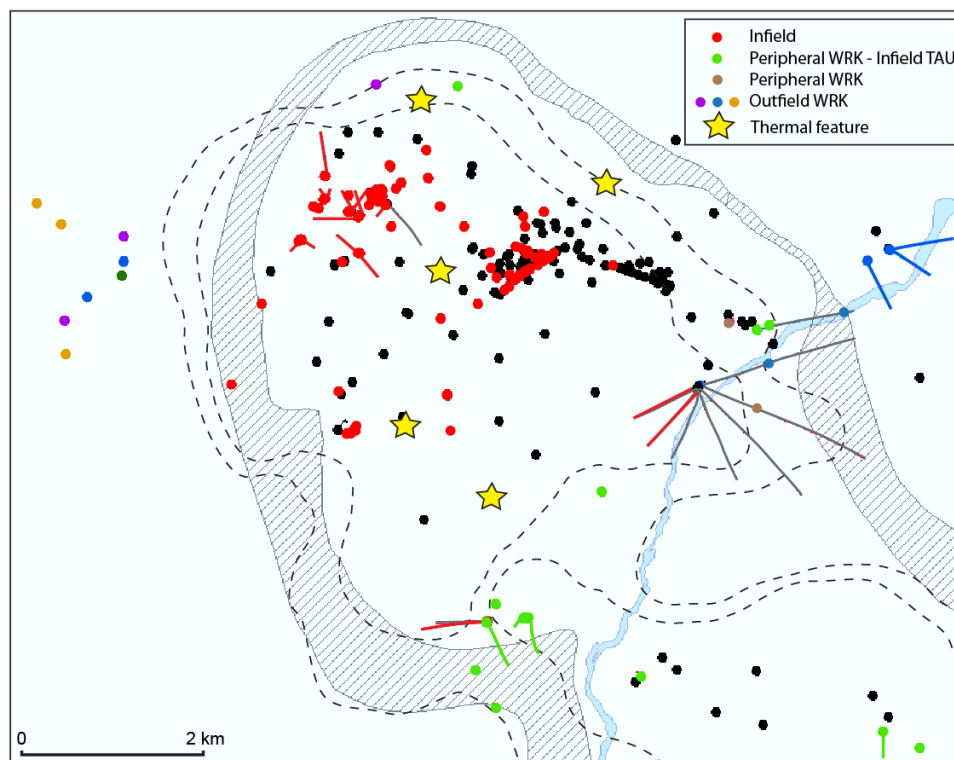


Figure 6. Reservoir pressure-based categorization of wells (color code as in Figure 5) and reservoir boundary interpreted from reservoir pressures, microseismicity and MT (dashed lines). Outer boundary approximates boundaries of the Wairakei-Tauhara geothermal system and inner boundary approximates separately boundaries of Wairakei and Tauhara. Thermal areas shown for reference.

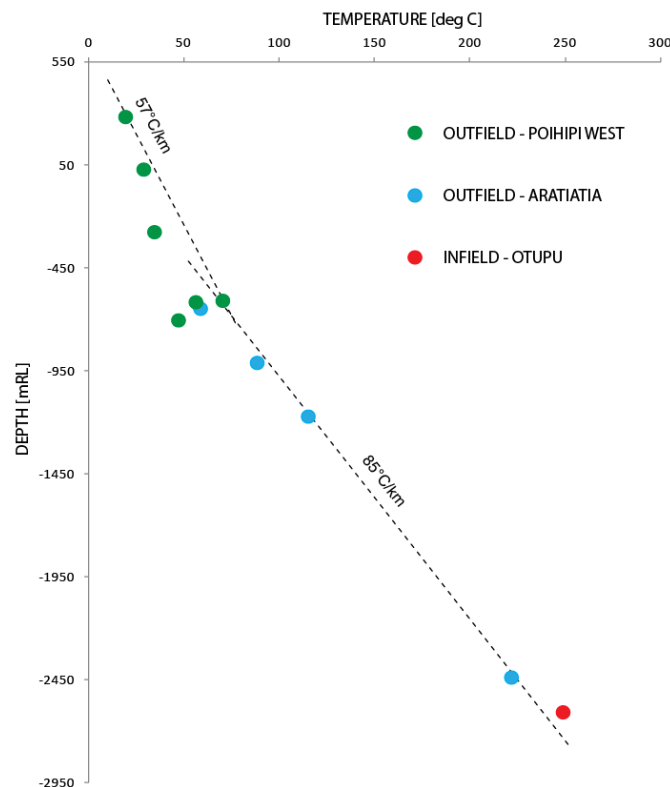


Figure 7. Maximum well temperatures versus depth for selected outfield wells (relative to the interpreted reservoir boundary in Figure 5). One infield well from the Otupu area shown for reference.

2.4 Magnetic anomalies

Ideal conditions under which magnetic anomalies can map a high-temperature reservoir include the existence of host rocks with originally high magnetization, and the occurrence of hydrothermally induced de-magnetization. Soengkono (2013) presented a recent review of regional magnetic anomalies of the TVZ and closely explored the correlation with surface geology. This study corroborated the correlation of magnetic highs with exposed lavas and ignimbrites. These rocks are abundant in the subsurface stratigraphy of Wairakei (0-3 km depth nominal) suggesting favorable conditions for the use of magnetic anomalies. With the Earth's last magnetic reversal situated at ~0.78 Ma (e.g., Dobrin et al., 1988), the likely time span of TVZ volcanism (~2.4 Ma; Wilson et al., 2010), and the intersection of the voluminous ~0.34 Ma Wairakei Ignimbrite at depths as shallow as ~600 m depth in the Wairakei field, suggests alternations of reversely and normally magnetized rocks prevailing within the deeper stratigraphy of Wairakei. Demagnetization of reversely magnetized rocks is unlikely to be a major contributor to magnetic lows.

Based on low resolution magnetic anomalies measured in early 80's at Wairakei (Soengkono and Hochstein, 1992), a series of magnetic lows were identified. Preliminary 2-D modeling of these anomalies situated sources of magnetic lows at depths ≤ 1.5 km. This result was relatively consistent with the hypothesis of magnetic lows mainly sourced from shallow demagnetized volcanic rocks with original normal magnetization. Figure 8 shows a reduced-to-pole (RTP) magnetic map of Wairakei from a high resolution airborne magnetic survey carried out in 1990. The main magnetic lows, highlighted in Figure 8, extend beyond the resistivity boundary in the western margin of the field, suggesting a pattern similar to that of MT anomalies. Based on drilling evidence from Poihipi West (see Figure 1), Sepulveda et al (2012) tentatively interpreted these magnetic lows as due to relict demagnetization. With the advent of microseismicity, a spatial correlation of these magnetic lows with deep microseismicity anomalies has become apparent (Figure 8). A series of low pass filtering techniques (e.g., Dobrin et al., 1988) were recently carried out on the magnetic data in Figure 8. The preliminary results show that the main magnetic lows can still be recognized at 15 km cutoff wavelength, suggesting that their sources could actually be extending to more than 3 km depths. Further 3-D modeling is to be carried out to test the possibility of deeper sources of low magnetization.

3. FINAL REMARKS

This study illustrates the utility of a multidisciplinary approach to interpret a modern reservoir boundary. In order to overcome potential limitations of conventional DC resistivity mapping, we presented an analysis of the resistivity structure down to ~700 m as derived from MT models in conjunction with some drilling evidence. Our conclusion is that MT remains a primary indicator of permeability. Microseismicity, which presently provides a deeper penetration relative to MT, was also discussed. Some common patterns are observed between the shallow MT conductor and microseismicity anomalies at depths of 500-3000 m, particularly, the correlation between lack of microseismicity and presence of low resistivity anomalies in the southeast margin of Wairakei near the transition with Tauhara. Both datasets suggests a continuity of these geophysical anomalies across Wairakei-Tauhara near the Karapiti area.

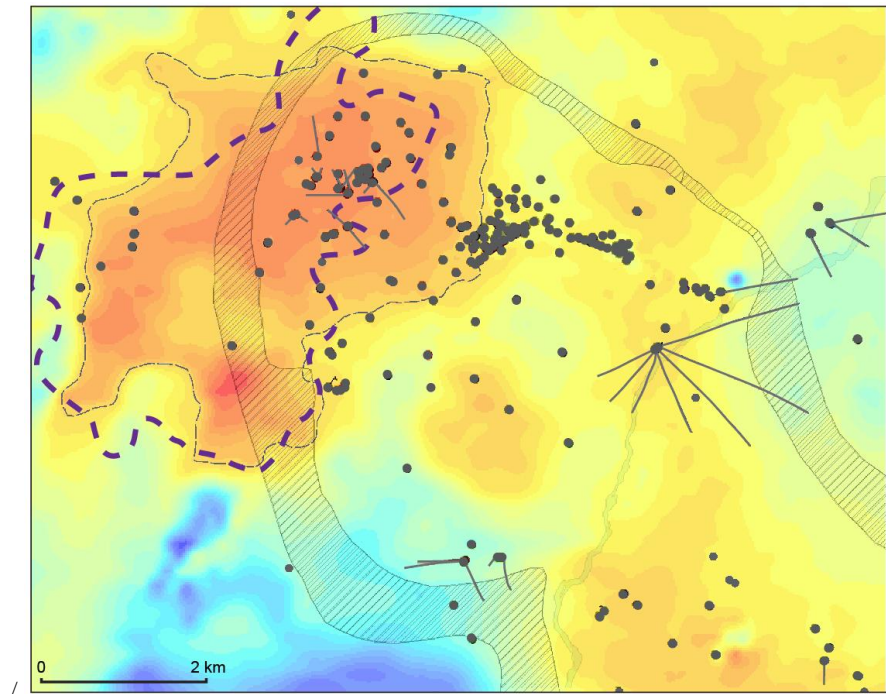


Figure 8. RTP magnetic map of Wairakei showing magnetic lows (orange to red colors) which are highlighted by a thin dashed line using the -200 nT contour. The outline of deep microseismicity as in Figure 3b (thick dashed line) is shown for comparison.

Reservoir pressures provide the most accurate picture of reservoir boundaries due to production-induced changes with time. However, the spatial coverage of well data is limited and geophysical information is used accordingly to bridge the gaps in well information. We found that it is possible to outline a reservoir boundary representative of 500-3000 m depths which is relatively consistent with all datasets (microseismicity, MT, reservoir pressures). At the same time, 3-D complexities of the Wairakei geothermal system are evidenced through this study highlighting that any attempt to outline a boundary in 2-D unavoidably needs to incur simplifications. Although the boundary of the Tauhara field is beyond the scope of this study, the field wide perspective adopted here lead us to encompass the northern boundary of Tauhara in our interpretations.

A strong shift in the foci of microseismicity towards the NW margin supports the hypothesis of a deep upflow near the NW margin (relative to the shallow boundaries). We have also recognized a close correlation of deep microseismicity with magnetic anomalies, which are to be further investigated via 3-d modeling.

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REFERENCES

- Bignall, G., Milicich, S.D., Ramirez, L.E., Rosenberg, M.D., Kilgour, G.N., Rae, A.J. Geology of the Wairakei-Tauhara Geothermal System, New Zealand. *Proceedings, World Geothermal Congress, Bali, Indonesia*, 8 pp (2010).
- Bertrand, E. A., Caldwell, T. G., Hill, G. J., Wallin, E. L., Bennie, S. L., Cozens, N., Onacha, S. A., Ryan, G. A., Walter, C. Zaino, A. and Wameyo, P. Magnetotelluric Imaging of Upper-crustal Convection Plumes Beneath the Taupo Volcanic Zone, New Zealand, *Geophysical Research Letters*, 39, (2012), L02304, doi: 10.1029/2011GL050177.
- Bibby, H. M., Caldwell, T. G., Davey, F. J., Webb, T. H. Geophysical evidence on the structure of the Taupo Volcanic Zone and its Hydrothermal Circulation. *Journal of Volcanology and Geothermal Research*, 68, (1995), 29-58.
- Bixley, P. F. Alternative Boundary Concepts for Geothermal Fields, *Proceedings, New Zealand Geothermal Workshop, Rotorua, New Zealand* (1994).
- Bixley, P. F., Clothworthy, A. W., and Mannington, W. I. Evolution of the Wairakei geothermal reservoir during 50 years of production. *Geothermics*, 38, (2009), 145–154.
- Brown, K. L., Henley, R. W., Glover, R. B., Mroczek, E. K., and Plum, H. Dilution and Boiling in the Wairakei Field due to Exploration 1959-1982. *Proceedings, New Zealand Geothermal Workshop, New Zealand* (1988).

- Bryan, C. J., Sherburn, S., Bibby, H. M., Bannister, S. C. and Hurst, A. W. Shallow seismicity of the central Taupo Volcanic Zone, New Zealand: its distribution and nature. *New Zealand Journal of Geology & Geophysics*, 42, (1999), 533-542
- Correa, N. A., Rae, A. J., Sepulveda, F. Distribution of Clay Minerals through a Conductive (MT) Zone on the Margins of a High-Temperature Geothermal Reservoir, Wairakei Geothermal Field, Taupo Volcanic Zone, New Zealand, *GRC Transactions*, Las Vegas, USA (2013).
- Dobrin, M. B. and Savit, H. *Introduction to Geophysical Prospecting*, McGraw Hill International Editions, 4th edition, 867 pages (1988).
- Gunderson, R., Cumming, W., Astra, D. and Harvey, C. Analysis of Smectite Clays in Geothermal Drill Cuttings by The Methylene Blue method: for Well Site Geothermometry and Resistivity Sounding Correlation, *Proceedings*, World Geothermal Congress, Kyushu – Tohoku, Japan. pp. 1175–1181 (2000)
- Hunt, T. M., Bromley, C. J., Risk, G. F., Sherburn, S., and Soengkono, S. Geophysical Investigations of the Wairakei Field, *Geothermics*, 38, (2009), 85–97.
- Milloy, S. F and Wei Lim, Y. Wairakei-Tauhara Pressure Regime Update. *Proceedings*, New Zealand Geothermal Workshop, Auckland, New Zealand (2012).
- Risk, G. F. Electrical resistivity survey of the Wairakei geothermal field, *Proceedings*, 6th New Zealand Geothermal Workshop, Auckland, New Zealand, 6, 123-128 (1984).
- Rowland, J. V. and Sibson, R. H. Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. *Geofluids*, 4, (2004), 259–283.
- Rowland, J. V., Wilson, C. J. N., and Gravley, D. M. Spatial and temporal variations in magma-assisted rifting, Taupo Volcanic Zone, New Zealand, *Journal of Volcanology and Geothermal Research*, 90, (2010), 89-108.
- Sepulveda, F., Mannington, W. Charroy, J., Soengkono, S. and Ussher, G. Integrated Approach To Interpretation Of Magnetotelluric Study at Wairakei, New Zealand, *Proceedings*, Stanford Geothermal Workshop, Stanford, CA, USA (2012).
- Sepulveda, F. Andrews, J., Alvarez, M., Montague, T. and Mannington, W. Overview of Deep Structure Using Microseismicity at Wairakei, *Proceedings*, New Zealand Geothermal Workshop, Rotorua, New Zealand (2013).
- Soengkono, S. and Hochstein, A. Magnetic Anomalies over the Wairakei Geothermal Field, Central North Island, New Zealand, *GRC Transactions*, 18, 273-278 (1992).
- Soengkono, S. Distribution, Age and Hydrothermal Alteration of Quaternary Volcanic Rocks in the Taupo Volcanic Zone (North Island, New Zealand) Seen from High Resolution Airborne Magnetic Data, *Proceedings*, New Zealand Geothermal Workshop, Rotorua, New Zealand (2013).
- Stagpoole, V. M. and Bibby, H. M. Electrical Resistivity Map of the Taupo Volcanic Zone, New Zealand: Nominal Array Spacing 1000 m, 1:250 000, version 1.0. *GNS Science Publication*, Lower Hutt, New Zealand (1998).
- Ussher, G., Harvey, C., Johnstone, R., Anderson, E. Understanding the Resistivities Observed in Geothermal Systems, *Proceedings*, World Geothermal Congress, Kyushu – Tohoku, Japan. pp. 1915 – 1920 (2000).