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INTEGRATED MT AND NATURAL STATE TEMPERATURE INTERPRETATION FOR A CONCEPTUAL MODEL SUPPORTING RESERVOIR NUMERICAL MODELLING AND WELL TARGETING AT THE ROTOKAWA GEOTHERMAL FIELD, NEW ZEALAND

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ABSTRACT

Recent Rotokawa Geothermal Field case histories illustrate the value of combined interpretation of natural state temperature, MT-TDEM resistivity and hydrothermal alteration for building conceptual understanding at the development stage of a geothermal reservoir. Rotokawa Joint Venture, a partnership between Mighty River Power and Tauhara North No. 2 Trust currently operates 174 MW of generation at Rotokawa. Important conceptual elements that can be clarified in joint analysis of MT and natural state temperatures beyond what is typically feasible based on MT for exploration projects include; details of fluid upflow/outflow, influx and cross-flow paths of cooler groundwater, and permeability variations above and at the margins of the reservoir.

As part of a revision of the Rotokawa conceptual and numerical simulation models, 1D and 3D imaging of over 80 MT stations was combined with natural state temperature interpretations based on numerous pressure-temperature-spinner logs from 32 wells at Rotokawa. Geological information, particularly formation types, methylene blue (MeB) smectite clay analyses, and more general alteration mineralogy, was considered in both the MT and natural state temperature interpretation in an iterative process. Interpreted temperatures were initially reconciled between adjacent wells and then interpolated and extrapolated by hand contouring, using the 1D (TE-mode) and 3D inversion resistivity cross-sections and conductance maps as a guide. The product was a general 3D conceptual model of the field that was then integrated with other geology, geochemistry, geophysics and reservoir engineering data to form a more detailed 3D conceptual model. This conceptual model is being used to inform decisions regarding the numerical model of the reservoir, reservoir management and well targeting.

INTRODUCTION

The Rotokawa geothermal field is located within the Taupo Volcanic Zone (TVZ) on the north island of New Zealand (Figure 1). The resource potential of the Rotokawa field was first identified from numerous surface thermal features (fumeroles, steaming ground, acid sulphate features and bi-carbonate springs) and Schlumberger resistivity surveys. Exploratory drilling undertaken from 1965 to 1986 by the New Zealand government (RK1 – RK6, RK8) confirmed the presence of a large, high temperature (>300 ˚C) geothermal resource.

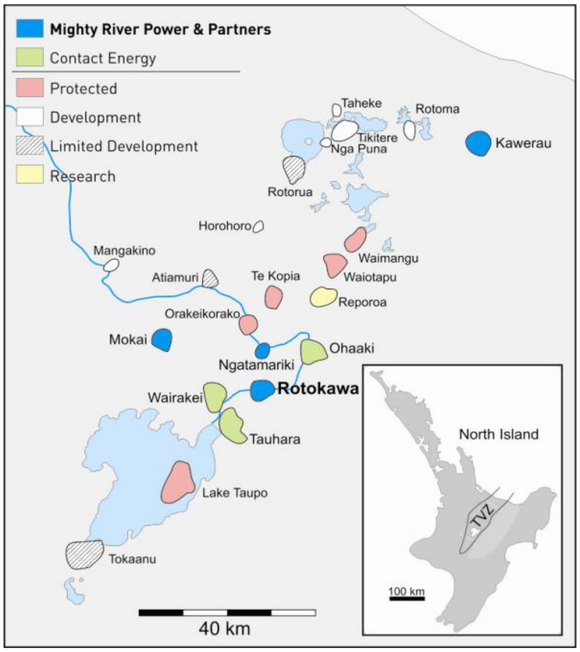

Figure 1 – Location of known geothermal fields in the Taupo Volcanic Zone (TVZ) on the north island of New Zealand. The Rotokawa field (bold) is approximately 12 km NE of Taupo, 10 km east of Wairakei geothermal field and 10 km south of the Ngatamariki geothermal field.

Electricity generation of 24 MWe began on the field in 1997 with the installation of the binary, RGEN plant. Production was initially from wells RK5 and RK9 with shallow injection into RK11 and RK12. In 2000, Mighty River Power and Tauhara North No. 2 Trust formed the Rotokawa Joint Venture and generation was subsequently expanded to 34 MWe. Shallow injection into RK11 and RK12 was shifted deep into RK16 and RK18 in 2005, based on a successful interpretation of the field margin based on 1D analyses of a subset of the current MT data set. In 2007, resource consents were obtained for a further development at Rotokawa, supported by conceptual and numerical modeling of the field based on production history (RGEN) and well results up to RK18 (Bowyer & Holt, 2010), supported by the earlier 1D and 3D analyses of the MT data, including that of Heise et al., (2008). The Nga Awa Purua (NAP) development began in 2008 with drilling of wells RK19 – RK30 and construction of a 140 MWe, triple-flash plant which was commissioned in May, 2010. Since then make-up production wells RK32 and RK33 have been drilled.

Following NAP start-up, a large project was commenced updating the conceptual and numerical models of the field. Significantly more information had been obtained since the last update in 2007, most importantly the information obtained from drilling of wells RK19 – RK32 and the initial response of the Rotokawa reservoir to greatly increased production and injection.

As part of the conceptual and numerical modeling effort undertaken in 2011, the natural state temperature interpretations and MT data were revised. The two were combined in an iterative process with supporting geoscience data to obtain nine deep and shallow conceptual elements that could be resolved using the available data and had explained reservoir features and, in several cases, the numerical simulation itself. These elements formed part of the overall conceptual model that was used to support a detailed numerical model that will be used to predict future reservoir response. The conceptual model will also be used to support reservoir management and future well targeting.

INITIAL NATURAL STATE TEMPERATURE INTERPRETATION

Initial natural state temperature interpretations were based mostly on available well PTS log data. However, measured well data can be significantly different to formation temperature for many reasons. Commonly encountered problems in natural state temperature interpretations that affected these wells included; insufficient heating periods to obtain steady state conditions, cross-flow in the well, persistent cooled zones following injection tests and changes in formation temperature from the natural state due to production-injection (Grant & Bixley, 2011). To mitigate related uncertainty, supporting information was incorporated into the initial natural state temperature interpretation including geology, mineralogy (XRD and MeB smectite measurements) and the interpreted top of reservoir elevation range from the MT (Figure 2).

Mineralogical temperature indicators are imperfect but provide useful information for natural state temperature interpretations, mainly as a means of checking interpretations (e.g. occurrence of bladed calcite underneath the smectite-illite transition suggests reservoir temperature is at boiling point at that depth). Smectite generally occurs at temperatures less than 200 ˚C (Ussher et al, 2000), although it is not a particularly good temperature indicator (Essene and Peacor, 1995) and can exist at significantly higher temperature, for example at 300 ˚C when dehydrated and sealed from further alteration (Gunderson et al., 2000). Smectite altered rock is typically impermeable, forming a ‘cap’ to most geothermal systems. The impermeable nature of rocks with significant smectite content, results in a conductive temperature profile in most cases.

Different wells drilled from the same pad often have measured temperature data points with less than 100m lateral separation. In these cases it is necessary to reconcile interpreted natural state temperatures to ensure consistency between wells. Where temperature data were within approximately 100m of each other, interpreted natural state profiles were chosen that were most consistent with all measured temperature data, all supporting geoscience data and with the general, previously established, conceptual ideas of the field (e.g. the Haparangi Rhyolite hosts a significant aquifer and is generally permeable).

MT-TDEM DATA AND INVERSIONS

Over 80 MT-TDEM stations have been acquired at Rotokawa (Figure 3). Following further surveying in 2010, MT coverage is now continuous from the Orakei-Korako field in the north, through Ngatamariki to Rotokawa. The total MT stations acquired over the combined area now exceeds 300.

Following additional data acquisition to the west of Ngatamariki in late 2010, a combined Ngatamariki-Rotokawa 3D inversion was completed. In total, 253 stations were incorporated into the inversion.

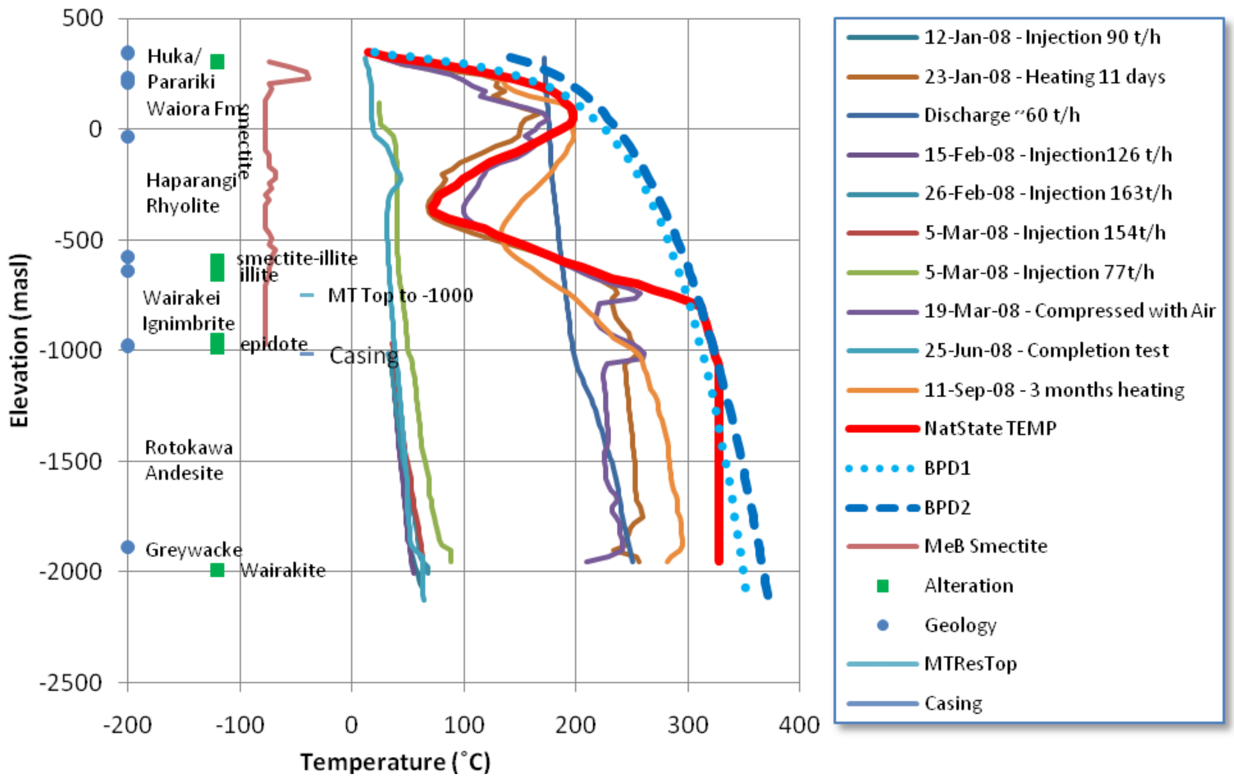

Figure 2. Example temperature and geoscience data used for interpreting natural state temperatures from RK20. Due to prolonged injection into the well prior to the 3 month heating period, a steady-state temperature profile has not been attained in RK20. Maximum temperature in the well is therefore inferred from nearby wells RK4, 24 and 22, all of which have maximum measured temperatures of 320-340 ˚C. The top of the reservoir (depth at which temperature becomes isothermal or intersects the BPD curve) coincides approximately with the interpreted reservoir top range from MT (range defined from 3D inversion resistivity sections) and the transition from smectite to illite observed in both XRD and MeB measurements. A conductive temperature profile is observed from approx. -800 to -400 masl which coincides with elevated smectite content and low resistivity in the MT. The natural state temperature above -500 masl in RK20 is taken from RK23 because RK23 and RK20 are drilled from the same pad and have separation less than 50m from surface to this elevation. The RK23 temperature profile was judged most representative of the natural state as it had a longer heating period and accurately represented likely flows within the intermediate aquifer (groundwater aquifer hosted mainly within the Haparangi Rhyolite and Waiora Fm). A conductive temperature profile with particularly high geothermal gradient is observed through the highly smectite altered Huka Falls and Parariki Breccia units that are known impermeable formations at Rotokawa.

In addition to the 3D inversion, 1D TE mode inversions of the data were undertaken. The 1D inversion approach offers several advantages over 3D inversion, particularly greater resolution in the near-surface and isolation of noisy stations from the inversion model. TDEM data was used to correct static-shift in the 1D inversions where appropriate. Both the 3D and 1D TE mode inversions were utilized in the interpretation, with more emphasis placed on the 1D TE inversion for shallow interpretation (approx. above sea level) and greater emphasis on the 3D inversion for interpretation of deeper elements to about -1000 masl. Both the 1D and 3D inversion appear to have poor resolution of resistivity features below approximately -1000m.

Deep conductors (<10 ohm.m) observed in the 3D inversion below approximately -1000m have been intersected by existing wells and no explanation for the conductors could be found in the wells. They also could not be interpreted in terms of any realistic conceptual model. It appears likely that the pattern of deep conductors and resistors is an artifact of the 3D inversion. For this reason, the resolution of features beyond approximately -1000m in the 3D MT inversion at Ngatamariki-Rotokawa is considered unreliable at this stage and is the subject of further research.

COMBINED 3D MT AND TEMPERATURE INTERPRETATION

Representative MT resistivity cross-sections and conductance maps were constructed from both the 1D TE mode inversion and 3D inversion (Figures 4, 5, 6, 7 & 8). MT sections were brought into a GIS package and manually contoured isotherms were digitized (every 20 ˚C). The isotherms were constructed using the natural state well interpretations, utilizing the MT resistivity cross-sections and conductance maps and the correlation of low resistivity with low permeability to interpolate and extrapolate between and away from wells. On occasion, inconsistencies in interpreted well temperatures were observed whilst constructing the isotherms which prompted a review of the borehole temperature interpretation, although the borehole temperature data was always considered the primary data set, with supporting data sometimes affecting the interpretation of conflicting well data.

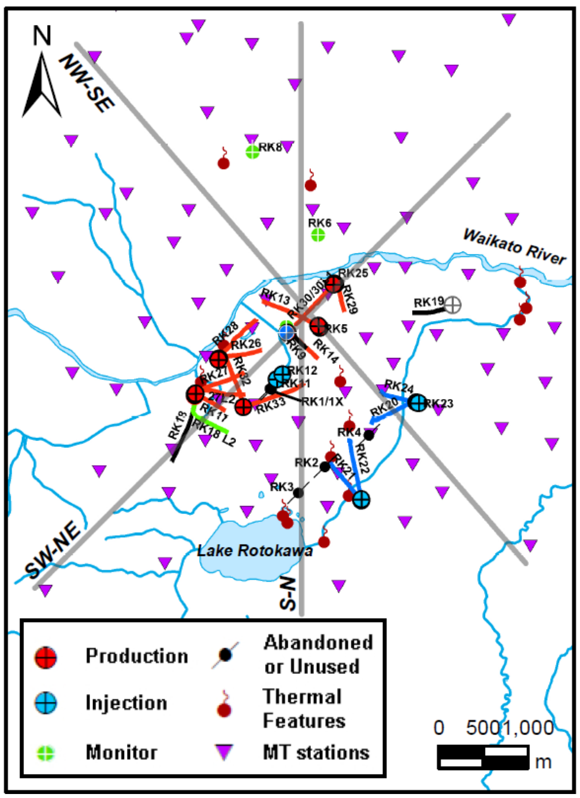

Figure 3. MT stations at Rotokawa acquired during several field campaigns from 2004-2010. Grey lines are cross-sections referred to in subsequent sections.

The isotherms hand drawn on the MT cross-sections were then imported as points into a 3D modelling package (MVS) and gridded as a 3D data space. Several iterations of identifying inconsistencies in the 3D model and refining cross-section temperatures were then performed. This ensured cross-section isotherms were consistent where they intersected and fit the conceptual pattern of flow constrained by thermodynamics and the mapped structures and geologic units that localize permeability. The final 3D temperature model provided an excellent match to interpreted well temperatures, MT and general conceptual ideas of the field.

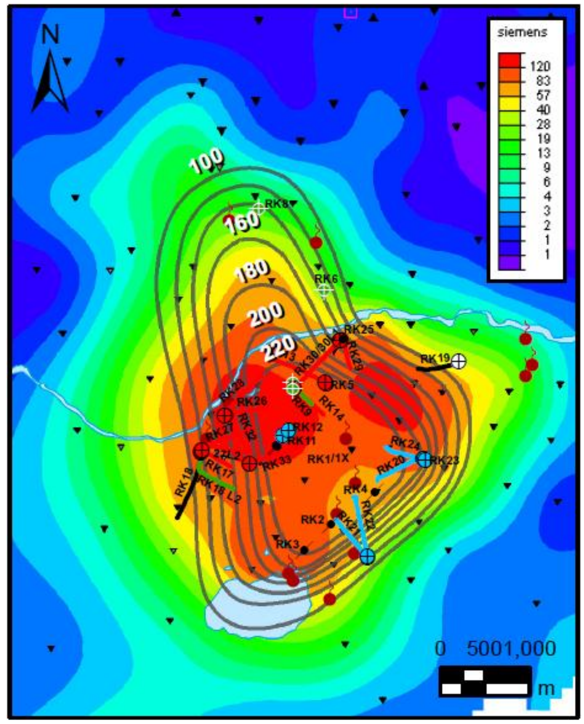

Figure 4. 1D TE inversion conductance from surface to 300m depth and maximum temperature within the intermediate aquifer. The extent of shallow, significant low resistivity (high conductance) approximately coincides with the 100 ˚C isotherm and the location of several thermal features. Isotherms are every 20 ˚C from 100-220 ˚C.

Gridding (2D and 3D) of only the well temperatures interpreted based only on the well log runs, whilst providing indicative trends in temperature, did not produce a conceptually consistent representation of the 3D temperature distribution. This is due to both the laterally sparse nature of the temperature data and the challenge of training gridding algorithms to interpolate and extrapolate temperature in a thermodynamically and conceptually consistent way. The process of manually constructing temperature cross-sections and reconciling the sections in 3D also provides a means of quality checking interpreted well temperatures and allows direct comparison with the 3D natural state temperature produced by numerical models.

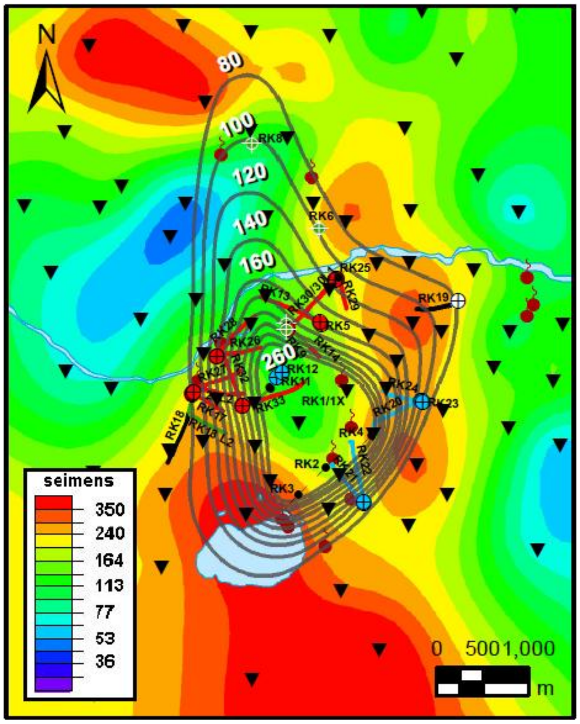

Figure 5. 3D inversion conductance from 0 to -1000m elevation and minimum temperature within the intermediate aquifer. Highest temperatures are observed in an area of relatively low conductance (high resistivity, green) surrounded by high conductance (low resistivity, red). This has been interpreted as a zone of low smectite content which may allow fluid flow into the intermediate aquifer from the deep reservoir. Isotherms are every 20 ˚C from 80-260 ˚C.

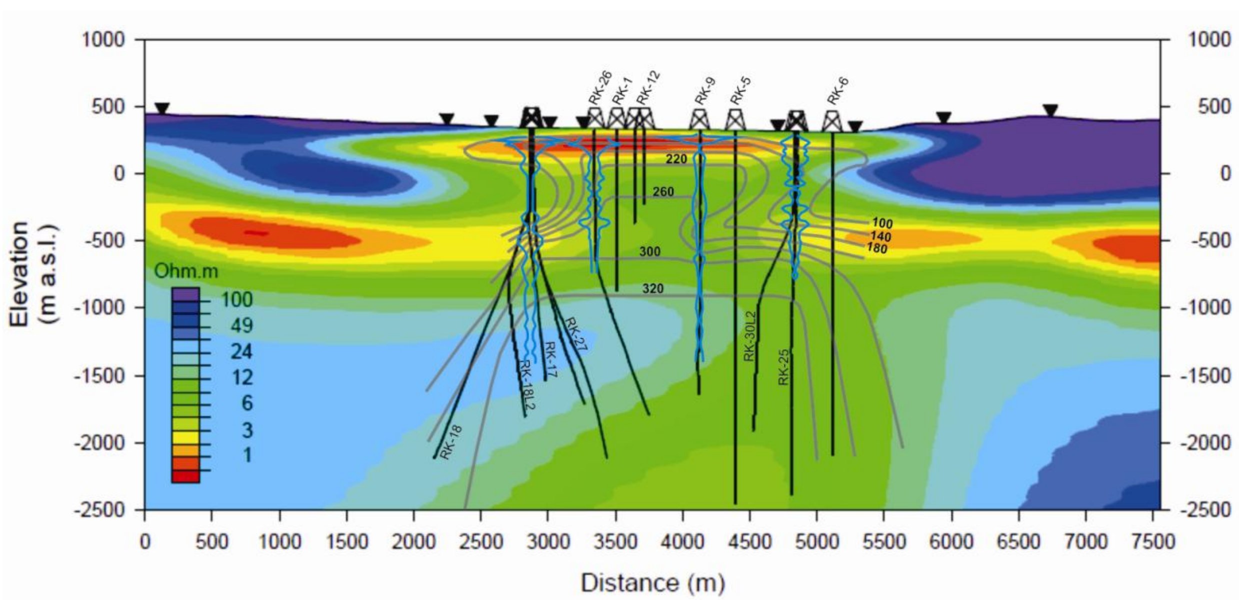

Figure 6. 3D MT cross-section SW-NE (see Figure 2 for location), isotherms and MeB smectite logs (blue). Isotherms are every 40 ˚C from 100-300 ˚C plus the 320 ˚C isotherm. Imaging of resistivity features below approximately -1000m in the 3D inversion are poorly resolved.

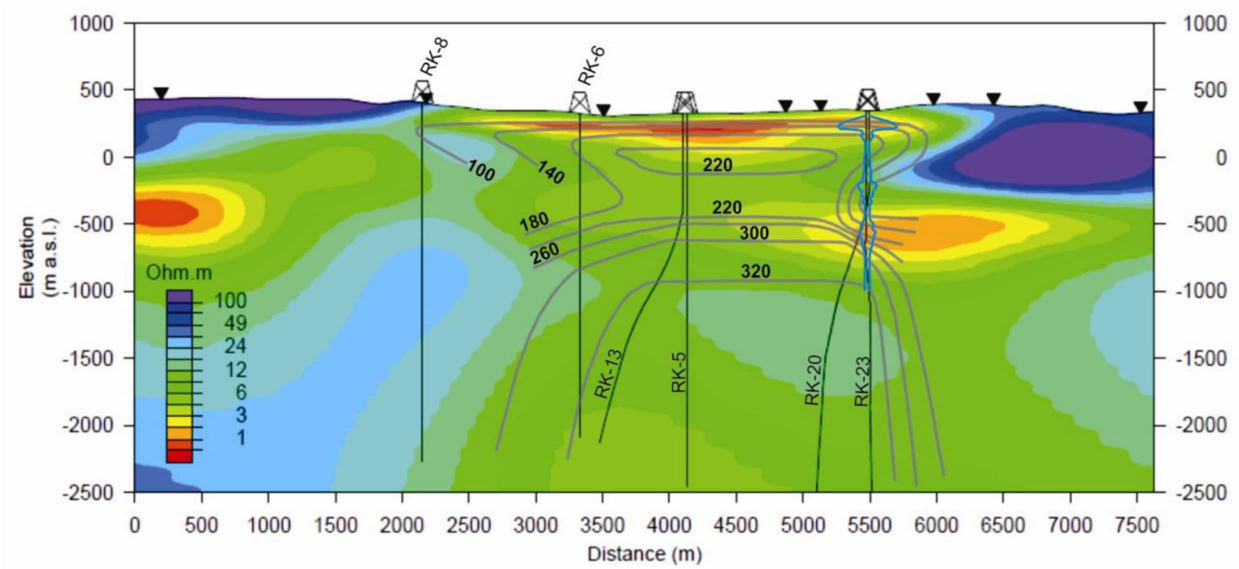

Figure 7. 3D MT cross-section NW-SE (see Figure 2 for location), isotherms and MeB smectite logs (blue). Isotherms are every 40 ˚C from 100-300 ˚C plus the 320 ˚C isotherm. Imaging of resistivity features below approximately -1000m in the 3D inversion are poorly resolved.

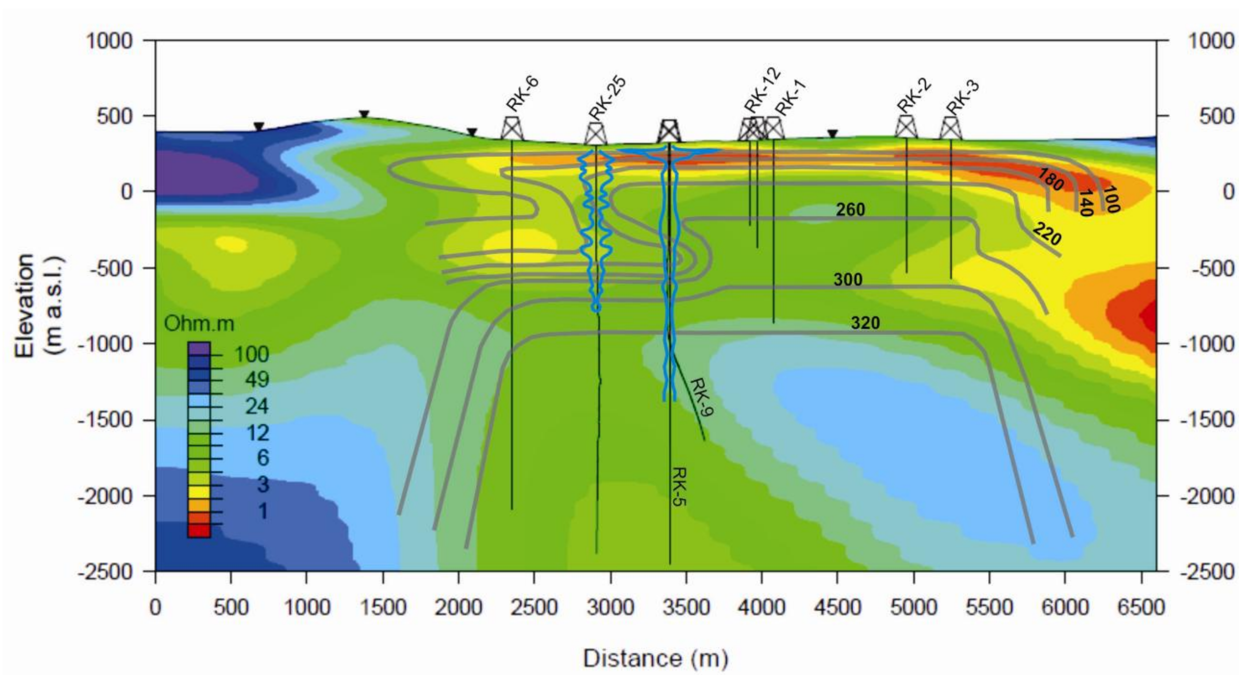

Figure 8. 3D MT cross-section N-S (see Figure 2 for location), isotherms and MeB smectite logs (blue). Isotherms are every 40 ˚C from 100-300 ˚C plus the 320 ˚C isotherm. Imaging of resistivity features below approximately -1000m in the 3D inversion are poorly resolved.

CONCEPTUAL ELEMENTS

The combined 3D MT and temperature interpretation was subsequently used to define a number of conceptual elements, mainly for the purposes of reservoir numerical modeling. They are shown schematically in Figure 9. These conceptual elements are consistent with other geoscience and reservoir engineering datasets available (geology, geochemistry, structure, microseismicity, gravity, reservoir pressure response, etc). They are divided into shallow (mostly above sea level) and deep (mostly below sea level) elements.

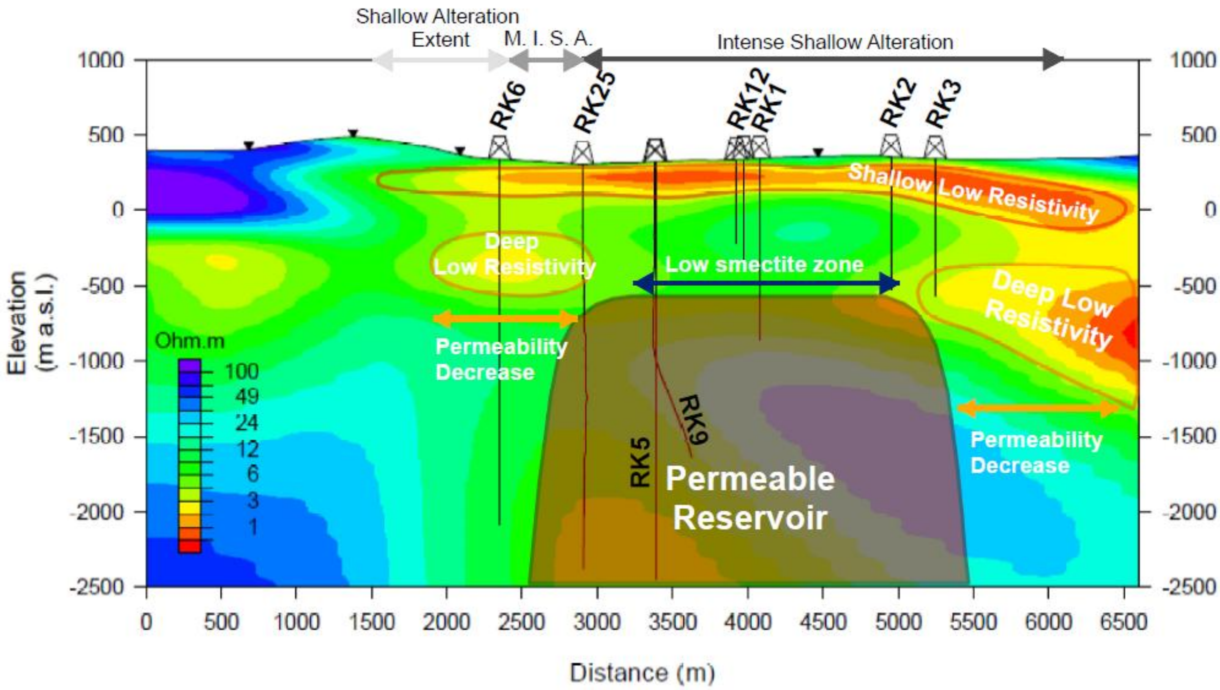

Figure 9. 3D MT cross-section N-S (see Figure 2 for location) and schematic, interpreted elements. M.I.S.A. = moderate intensity shallow alteration.

The shallow elements are:

Intense shallow alteration – area of shallow (~surface/water table to 0 m elevation), very low resistivity (generally <1 ohm.m) indicating relatively high smectite content, probably related to intense hydrothermal alteration. The intense smectite alteration in this zone is confirmed by MeB smectite measurements in wells. The alteration occurs largely within the Huka Falls (lacustrine sediments) and Parariki Breccia (hydrothermal eruption breccias) which together act as a shallow cap to the intermediate aquifer.

Moderate intensity shallow alteration – the resistivity in this zone is higher than the more intensely altered zone (generally 1-5 ohm.m), suggesting less smectite alteration and lower temperature. Again this is confirmed by well temperatures and MeB smectite measurements. Thermal features that appear in this zone (e.g. springs on the Waikato River), suggest that the shallow cap becomes thinner and slightly more permeable in this zone.

Shallow alteration extent – This is the extent of the shallow, significantly low resistivity layer (~ <10 ohm.m). Thermal features, in particular the steaming ground (both relict and current) to the north of Rotokawa, appear in this zone. Based on well temperatures, this may be taken as approximately the extent of >100 ˚C fluid at the top of the intermediate aquifer.

The deep elements are:

Permeable reservoir – high temperature (>300 ˚C), permeable, convecting reservoir. This has been interpreted mostly from well data (mostly natural state temperatures) and from the MT.

Permeability decrease - where permeability decrease occurs on the outer margin of the reservoir. Open fractures within this zone are less frequent and deeper. The MT data images a deep low resistivity layer from elevation 0 to below -1000 masl in this zone that is interpreted as a decrease in temperature and permeability related to an increase in smectite content. This is confirmed by wells on the edge of and within this zone that are observed to be either cooler (<300 ˚C) and/or to have deeper reservoir tops as indicated by the depth to which conductive temperature profiles are observed. The permeability decrease at the west, south and east margins of Rotokawa appear to be relatively sharp as indicated by the strong lateral temperature gradients and well permeabilities (e.g. RK17 to RK18L2 to RK18L1 and RK23 to RK20 and RK24). This suggests that the extent of the permeable reservoir may be controlled by faults acting as barriers as well as conduits to flow, a pattern consistent with the geology (O'Brien, 2011).

Low smectite zone – the available MT data suggests that the deep, low resistivity smectite alteration zone below sea level (the deep cap) is absent or significantly thinned over part of the field. This area is observed to have only a highly altered, intense low resistivity, high smectite content, shallow cap. Well temperatures in this zone also indicate lack of a well developed, thick, deep cap that is observed in other areas. However, extreme temperature reversals in wells like RK 5 (290 ˚C to 170˚C in approx. 100m) indicate that thin, impermeable formations and/or thin clay alteration layers are likely to be significant barriers to vertical flow in this zone. Well temperatures and precision gravity surveys indicate that significant shallow (approximately +200 to -300m elevation) 2-phase conditions existed in most of this area in the natural state. The lack of a thick, consistent cap in this zone results in higher shallow temperatures and, on average, better shallow horizontal permeability compared to areas with deep low resistivity. However, this does not imply that permeability is consistently high from the shallow cap down to the reservoir throughout this zone. Well temperatures, geochemistry and geology suggest that the main vertical, high permeability connection between the reservoir and intermediate aquifer, is probably in the southern part of the field and probably controlled by a known fault in that area (RK2/RK4 area) (Winick, 2011; O'Brien, 2011).

CONCLUSIONS

Careful integration of a 3D natural state temperature interpretation, 1D and 3D MT interpretations and relevant alteration mineralogy and geology has proven a highly effective tool for building a conceptual model of the Rotokawa reservoir. Initial natural state temperature interpretation was based mostly on measured well data, assisted by incorporation of relevant geological and geophysical information such as alteration mineralogy and interpreted MT reservoir top (base of low resistivity). Interpretations between adjacent wells were then reconciled if lateral separation between points was less than about 100m. Manual contouring of temperature on a representative selection of seven MT cross-sections was then completed, using the correlation of low resistivity with impermeable smectite clay as a guide when extrapolating and interpolating from the wells. Cross-section temperatures were then roughly reconciled and then digitized and iteratively adjusted to produce a consistent 3D distribution of natural state temperature in the MVS 3D visualization system. The combined MT and temperature cross-sections and maps could then be interpreted in terms of several deep and shallow conceptual elements, each with its own spatial, permeability and flow characteristics. The conceptual elements produced can be easily assimilated into reservoir numerical models and form a good basis for a more detailed conceptual model incorporating all other geoscience and reservoir engineering data that can be used for numerical modeling and reservoir management.

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