Formation Assessment in Geothermal Using Wireline Tools – Application and Early Results from the Ngatamariki Geothermal Field, New Zealand

Irene Wallis[1], Stephen McCormick[2], Steve Sewell[1] and Catherine Boseley[1]

[1] Mighty River Power Limited, PO Box 245, Rotorua 3010, New Zealand

[2] Petromac Ltd. 21 Hawke Crescent, Beachlands, Auckland, New Zealand

irene.wallis@mightyriver.co.nz

Keywords: *Reservoir Characterization, Wireline Logging, Petrophysics, Tahorakuri Formation, Poission's Ratio, Resistivity, Magnetotellurics*

ABSTRACT

In 2012/13 Mighty River Power (MRP) is conducting a wireline formation assessment program during the Ngatamariki 82MW development drilling. This includes wireline logging in the production section of all wells and intermediate section of one well. In this paper we describe the logging program – the tools used and their application. We also report on logs collected in one well section and the preliminary results of integrating these logs with data more commonly collected from geothermal wells, such as geology, temperature and drilling data. Results of the wireline formation assessment are being used throughout the development program for drilling decisions and optimization. These data are also being used to inform the construction and refinement of MRP's conceptual, geologic, geomechanical and numerical models of the Ngatamariki Geothermal Field.

1. INTRODUCTION

1.1 Wireline Logging in the Conventional Geothermal Industry

Formation assessment in-situ using wireline tools is common practice in the minerals and petroleum industries. However, these tools are rarely applied to geothermal developments primarily due to temperature limitations of tools, but perhaps also because there is incomplete understanding of how these tools respond to rocks in a hydrothermally altered, volcanic environment. The exceptions are pressure, temperature, spinner (PTS) tools and some borehole image tools which have been engineered to handle the high temperature environments. Relative to the number of geothermal wells drilled, very few logs have been run in New Zealand and most have been image logs (e.g., Wallis et al. 2012, McLean and McNamara 2010). A number of non-image wireline logs have been published from geothermal fields in Indonesia (e.g., Stimac et al. 2010), Iceland (e.g., Stefansson, Gudlaugsson and Gudmundsson 2000, Danielsen 2010), America (Sanyal et al. 1982) and the Philippine's (Vicedo et al. 2008), but to our knowledge the logs herein are the first publication of gamma, sonic, and resistivity log responses from a New Zealand geothermal field.

For the most part, the wireline logging technology used in geothermal is adopted from the petroleum industry where wells are cooler, dominantly hosted in sedimentary rocks and interpretation theory is well developed following decades of commercial log acquisition, interpretation and research. As such, there are three key challenges when running and interpreting wireline logs in geothermal: (1) the temperature limitations of available tools; (2) the abrasiveness of the volcanic rocks which impacts pad-type tools which require contact with the borehole wall, such as formation density; and (3) limited usefulness of standard oil & gas log interpretation procedures decoding log from a volcanic rock hosed system with dominantly fracture permeability, extensive secondary mineralization and different well hydraulics (filter cake, mud salinity etc.). The first two challenges are being managed in our program using a combination of strict operational control and trade-off between desired logs or tool set-up against the risk of tool damage. The third challenge is the subject of current and ongoing work at MRP.

1.3 The Ngatamariki Wireline Program

The Ngatamariki geothermal field is located approximately 25 km north-east of Taupo, New Zealand. MRP is currently drilling production and injection wells to support an 82MW binary plant which is due to be commissioned in 2013. In this paper we present the first wireline logs collected at Ngatamariki during this development, which includes gamma-ray, array induction, dipole sonic and oriented caliper. These logs were run in the intermediate section of NM8 (a 3500 m injection well) and cover the Tahorakuri Formation (Figure 1). This formation is a relatively poorly understood pyroclastic succession with least two district pyroclastic units identified to date which are overlain by a sedimentary succession (Chamberfort and Bignall 2011, Boseley et al. 2010). The logged section of NM8 is coincident with the alteration halo of a diorite magmatic intrusion. Secondary mineralization in this halo is dominated by a phyllic assemblage (quartz, pyrite, illite, chlorite and muscovite/sericite) and in places completely destroys primary rock textures (Lewis, Chamberfort and Rae 2012, Christenson, Wood and Arehart 1998) As there was near total-returns of drill cuttings to surface throughout the NM8 intermediate section, this interval has offered us a valuable opportunity to assess the log responses against cutting returns.

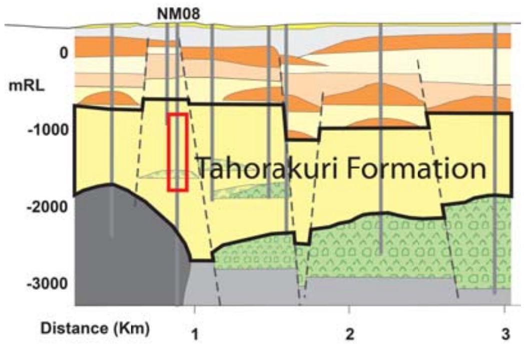

Figure 1. stratigraphy of the Ngatamariki geothermal reservoir. Note that the central part of the reservoir is dominated by the Tahorakuri Formation. Red box highlights the depth in NM8 over which wireline logs were run.

We designed the wireline program to provide information that would inform the construction and updating of conceptual, geomechanical, and reservoir numerical models – tools for resource management. It was, however, also set up to test a number of tools. The program therefore includes running a variety of standard temperature rated tools (150-177°C), some of them for the first time in the Taupo Volcanic Zone (TVZ), as well as high-temperature tools such as pressure, temperature spinner (PTS) tools and Tiger Energy Service's acoustic image tool (AFIT).

2 LOGS COLLECTED IN NM8

Schlumberger's array induction, gamma-ray, dipole sonic and oriented caliper tools were run in NM8 from 1170 to 1950m. All logs in this paper are presented in Measured Depth (MD) as measured along the well track from the drill floor (7.86 m above ground level). The intervals above 1215m and below 1920m were excluded from analyses because, due to the length of the tool string not all logs cover the lower part of the hole record and in the upper part the borehole conditions were so poor log responses were deemed un-interpretable.

Array Induction (Resistivity)

The Array Induction (AI) tool measures formation conductivity. The principal outputs are electrical resistivity at nominal depths of investigation from the borehole (10", 20", 30", 60" and 90"). Where the drilling mud has a different resistivity to formation water, permeable rock can be identified by separation between deep and shallow (i.e., 10" vs. 90") reading measurements because of the mud filtrate invasion. Correspondingly, deep and shallow resistivity logs will overlay in impermeable rock because there is no mud filtrate invasion. It is important to note, however, that this log is sensitive to borehole size and therefore has to be considered along with a caliper log.

Spontaneous potential (SP) is a detector included in the array induction tool which measures the naturally occurring electrical potential (voltage) in the borehole referenced to a surface electrode. Spontaneous potentials are usually caused by charge separation in clay or other minerals, by the presence of a semi-permeable interface impeding the diffusion of ions through the pore space of rocks, or by natural flow of a conducting fluid (e.g., salty water) through the rocks. SP may have use in delineation of bed boundaries and identification of zones with active fluid loss, but further work is required to understand this log response in the geothermal environment.

Gamma Ray

The gamma-ray (GR) tool measures gamma-ray radiation from the formation. Naturally occurring radioactive elements are potassium, thorium and uranium. In sedimentary rocks, high GR is typically associated with clay occurrence. In volcanic rocks many of the rock minerals are naturally radioactive due to the relatively high proportion of potassium bearing minerals (e.g., alkali feldspars). In a geothermal environment, where extensive secondary mineralization is present, the GR would detect a composite of the primary lithology and the alteration, particularly clays and adularia. GR response is typically used for stratigraphic correlation. However, this usage is complicated in geothermal because of the secondary mineralization.

GR logs may have future applicability to mapping permeability in geothermal. Adularia, which is a common secondary mineral in geothermal associated with permeability, has a high (around 12.7) weight % of potassium (Serra 1990). Although most alkali feldspars have a similar level of potassium, a concentration of adularia in the formation should result in an increased GR response. However, further work is required to characterize log responses to hydrothermal alteration before it will become a useful predictive tool. Due to the systematic variation of potassium, uranium and thorium content in minerals, GR response can some cases be used for mineral identification. However, where mineral identification is a primary goal, spectral gamma is more typically run rather than a tool that just collects total gamma as has been used in NM8.

Dipole Sonic

The dipole sonic tool records the full sonic wave-form including compressional (Vp) and shear (Vs) waves. Transmitters in the tool generate a pressure pulse which radiates through the mud column where it is refracted along the borehole wall. The pulse wave-train is recorded by an array of receivers regularly spaced along the tool length. By matching the recordings from each receiver – slowness travel time coherence processing – the sonic velocity is determined. Shear velocity is determined in a similar fashion, but uses dipole transducers and receivers. These transducers focus and receive energy perpendicular to the borehole wall, thereby enhancing the shear wave signal. This tool can also be set to record the Stoneley wave, otherwise known as a tube wave, which is the high amplitude wave that travels along the borehole wall at the rock-fluid interface.

Primary porosity can be estimated from Vp, but lithology specific transforms are required. These empirical relationships are commonly used for sedimentary rocks, but none have been located for silicic volcanics and work is underway to fill this gap (c.f., Wyering et al. this volume). Vp and Vs, particularly in conjunction with rock density, can be used to quantify the elastic moduli, including the relative rock stiffness (Young's Modulus). These in turn can be applied to drilling optimization, fracture and well stimulation modeling, as well as wellbore stability studies. A number of algorithms exists for converting Vp and Vs data to unconfined compressive strength (Chang, Zoback and Khaksar 2006), but these conversions also suffer from being lithology specific and we have been unable to locate any for silicic volcanic rocks.

Geological Logs

In order to understand the log responses, we began with a detailed re-look at drill cuttings over the logged interval. The cuttings were re-logged taking note of changes in primary lithology, alteration and changes in the physical character of the cuttings. The latter was used to infer variation in the mechanical nature of the rock where bulbous and somewhat rounded cuttings are generally less indurated than those with a platy and angular morphology. Based on the re-log, we divided the logged interval into a number of physical units (PU) which could then be correlated to log responses (Figure 2). The lithologic log in Figure 2 was constructed by the well-site geologists based on observations of the underlying lithology (Lewis et al. 2012).

3 RESULTS OF COMPARISON BETWEEN GEOLOGY AND WIRELINE LOG RESPONCES

The first half of this section will discuss log responses by depth broadly in three groups: PU0-3, PU4 and PU5, and finally PU6-16. The second half focuses more on picking out which physical groups and lithologies have district log responses utilizing two kinds of cross-plot. There is a great amount of detail in these wireline logs that, due to space limitations, we cannot touch on here.

Log responses by depth are presented in Figure 2 alongside two different kinds of formation log, the drilling fluid loss record, a normalized rate of drilling penetration (nROP) and a thermal gradient plot made from an injecting PTS run during the well completion testing. Despite the inevitable mixing of cuttings in the borehole, the interpreted physical units appear to generally match well (black dashed horizontal lines Figure 2). There are some refinements to the stratigraphic sequence which have been made and these have been represented on the strip log as red dashed lines (R1-R7 in Figure 2).

Physical Units 0-3

These units, which are comprised of tuff breccia (lithology A in Figure 2), include a stepwise change around 1280 m, and a relatively consistent log response above and below this point. The stepwise increase in AI and sonic velocity, and decrease in GR, is accompanied by a visible change in the cutting morphology, from somewhat rounded (bulbous) to more plate-like cuttings, and a short period of increased nROP. Drilling fluid losses increase across PU2 and PU3, but there is little change in the thermal gradient over this interval. The absence change in thermal gradient in this zone may, however, be due to: (A) a large amount of drilling fluid exited the formation at this point during drilling and the zone had not re-heated when the completion testing was run or (B) the permeability in this zone is not great enough to have an impact on the temperature though casing during a 55 t/hr injection rate test. A PTS profile that is planned for after this well has been shut for period will hopefully provide more information about permeability in this intermediate interval on NM8.

Physical Units 4 and 5

PU4 is very distinct because the material retuned to surface is dominantly comprised of fine grains of cubic pyrite, occasional well-formed euhedral grains of quartz and very rare, fine cuttings of tuff. The volume of tuff returned to surface increases toward the base of PU4 allowing the geologic identification of this unit as a tuff breccia. This sample also has a high proportion of lost circulation material (LCM) contamination because it coincided with operational efforts to plug losses to the formation. PU4 also coincides with the most distinct feature in the wireline log: very slow sonic velocities, very low resistivity and a kick followed by sudden decrease in GR. There are a number of factors that would influence these log responses including relatively high porosity (lowers velocity and resistivity and gamma), high clay content (lowers velocity, resistivity and gamma), poorly cemented tuff (lowers velocity), and the presence of abundant pyrite in parts (lowers resistivity). It’s difficult to distinguish, however, the relative contribution of each of the factors to the log response without closer analysis of the mineral abundance and further work is required here. The SP also shows a distinct increase over this zone which may also be explained by the differing electrical conduction mechanisms of high porosity/smectite/pyrite (i.e., ionic, cation exchange, electronic mechanisms respectively). Taken together, this log response indicates an increase in alteration and a history of persistent hydrothermal fluid flow.

PU5 comprises welded ignimbrite. It has a gradational increase of sonic velocities toward the base which could be interpreted as a decrease of porosity perhaps due to an increase in welding, compaction or secondary mineralization in-filling pore spaces. This change is mirrored by in gradually increasing resistivity, either related to the porosity decrease or an increase in conductive minerals. There is no separation between the AI10’’ and AI90’’ log responses in PU5 (between R3 and R4) and the sonic log response is very fast. The resistivity in this interval is significantly lower than what would typically be expected from such fast rock. In a sedimentary basin environment this style of log response would be attributed to the presence of conductive framework minerals and interpreted as shale. In the NM8, this log response is coincident with a welded ignimbrite containing rare veining and rare jig-saw breccia that, as mentioned above, has a gradational change from top to bottom. Drilling fluid losses were relatively high throughout this interval despite operational efforts to heal losses LCM. This could be taken to indicate increased permeability. However, there is no significant increase in the thermal gradient in PU5. This miss-match in permeability indicators would be due to the reasons described for PU0-3.

The exact depth of the contact between the welded ignimbrite and overlying tuff breccia is difficult to confidently locate based on cuttings alone. No cuttings were collected for 1415 m, most likely due to increased fluid loss to formation, and cuttings from 1395-1410 are extremely fine. The fine cuttings in this interval make it difficult to interpret without XRD or thin-section, and material collected has suspect depth control. Furthermore, drilling records show that the well tool a quick drink (i.e., a short, sudden increase in the losses of drilling fluids to the formation) at around 1425 m which would have temporarily changed the fluid dynamics inside the wellbore. This would have impacted the way cuttings are returned to surface and likely increased mixing of material in the well thus further decreasing cutting depth confidence. The log responses, however, tell a much clearer story because they are not susceptible to the depth uncertainty inherent in cutting analysis. We have therefore been able to confidently pick the top of the welded ignimbrite at 1410 mD (R3 in Figure 2).

Physical Units 6-16

PU6 to PU16 covers the lower part of the welded ignimbrite and a sequence of tuffs, volcaniclastics, and tuff breccias. Over-all this sequence consists of fast sonic velocity and high resistivity log responses, and both likely due to low porosities. From around 1590 m (base of PU9) there is separation between the AI10’’ and AI90’’ logs and at the interpreted top of the vein-tuff breccia (R5 in Figure 1) there is a stepwise increase in the magnitude of this separation. R5 is also coincident with a step-wise change in GR. If the mud filtrate was more saline than the formation water then we could infer that formation below R5 has increased near well-bore permeability because there has been mud invasion into the formation. However, in NM8 the drilling fluid had a similar salinity to the formation water, so it is not conclusive that mud invasion is the process causing the log separation. This uncertainty aside, the increased positive variation in the temperature gradient from R5 down supports our interpretation that this zone has increased permeability, as does the coincident increase in drilling fluid losses over this interval.

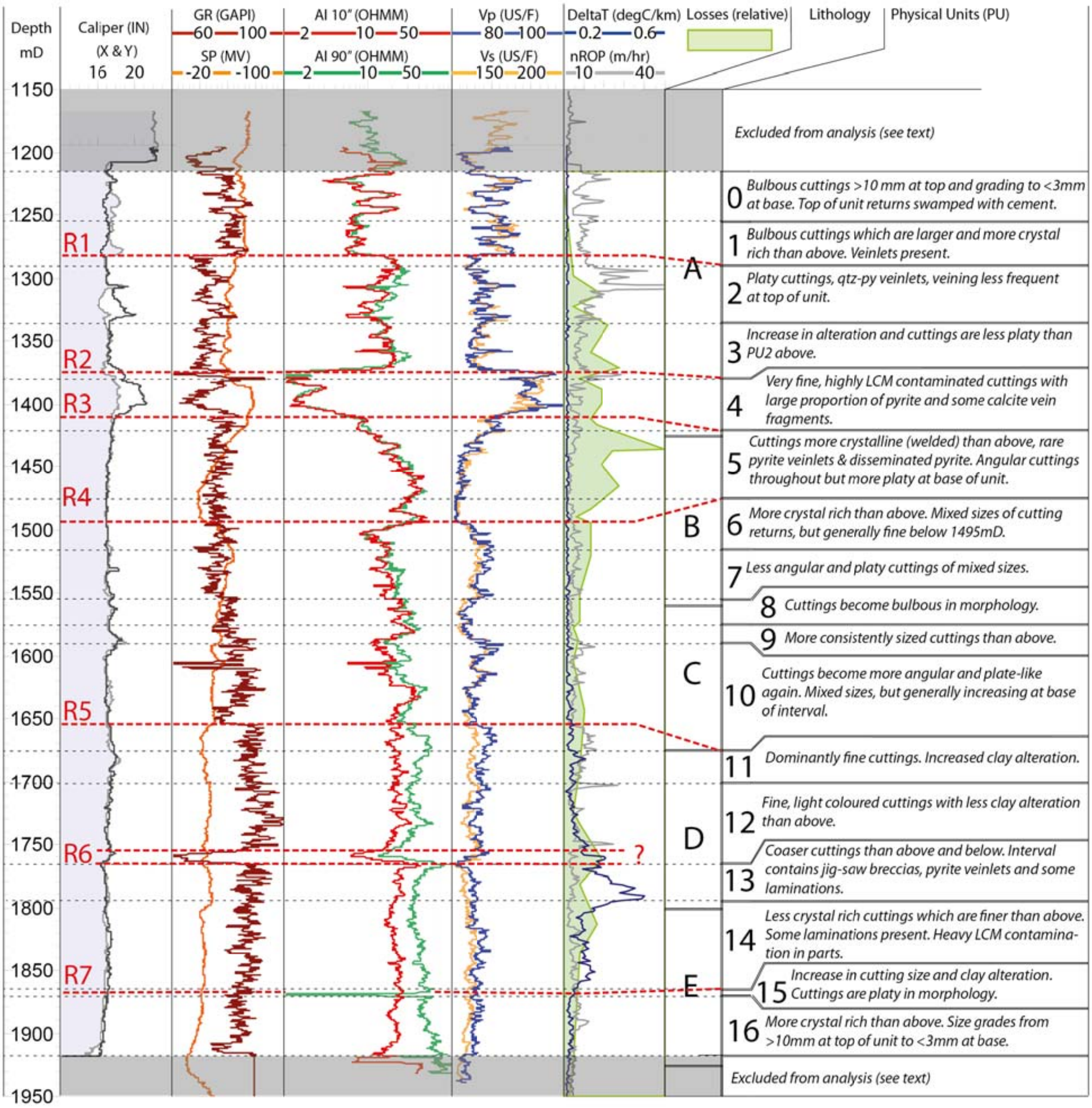

Figure 2. A strip log containing, from left to right, X and Y direction caliper (bit size is 17''), spontaneous potential (SP), natural gamma-ray (GR), resistivity (AI) at two depths of investigation (logarithmic scale), shear (Vs) and compressional (Vp) sonic velocities (as shear slowness), drilling fluid losses, normalized rate of penetration during drilling (nROP), thermal gradient (deltaT), lithology (where A = tuff breccia, B = welded ignimbrite, C = tuff and volcaniclastic breccia, D = vein-tuff breccia and E = crystal-poor tuff), and physical units (0-16). Black dashed lines delineate the contacts between physical units as they were identified using drill cuttings. Red dashed lines demarcate the refinement of these contacts based on log responses. Refinement 6 (R6) is questioned as it is likely that the inflection in the log responses at this depths should be split out as a unit of its own. The drilling fluid losses record is influenced both by well permeability and drilling operations to heal these losses. Note that an increase in losses at a given bit depth may in fact be the reopening of losses further up the well. Thermal gradient (DeltaT) was calculated using a 55 t/hr injecting PTS profile collected during the well completion testing. At the time the 17'' section of NM8 was behind casing, so responses are expected to be muted. nROP is the drilling rate of penetration normalized for changes in bit RPM and the weight on bit, and therefore is somewhat representative of changes in formation (provided by Lewis et al. 2012). However, bit wear, hydraulics and vibration has not been accounted for in the normalization so there not be a one-to-one correlation between nRPO and the changes in mechanical nature of the formation.

Cross-plot Analysis

Cross-plots are a common method of analyzing log data because they can be used to visualize a particular log response in two or three dimensions, and can present large volumes of data. There are a number of standard cross-plots used in sedimentary reservoirs to characterize lithology and mineralogy. Two simple cross-plots have been presented here that show variation of log response due to change in formation – one presents sonic velocities plotted against lithology/physical unit and another plots Vp against deep resistivity (AI 90'') with data grouped by physical unit.

The lower plot in Figure 3 is a cross-plot of Possion's ratio against formation change. Possion's ratio (υ) is the elastic moduli which describes the ratio of lateral expansion to axial shortening of a material in response to compressional or extensional forces (Zoback 2007). This ratio can range between an observed lower limit of 0 (cork) and a theoretical upper limit of 0.5 (rubber) – where quartz typically has a value of 0.167 and obsidian 0.185 (Gercek 2007). This ratio can be derived from Vp and Vs using the following relation:

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

Values for Poisson's ratio in NM8 varied between 0.1 and 0.38, with a median of 0.24. The upper plot in Figure 3 is a cross-plot of the ratio of compressional to shear wave velocity (Vp/Vs) against formation change. This ratio is commonly used as a lithology indicator in sedimentary environments and is dependent on the Poisson's ratio for a given material (Gercek 2007).

Both the upper and lower plots in Figure 3 show that there are two relatively distinct parts to the logged interval and the contact between these parts occurs at the base of PU5 (indicated by black arrow on Figure 3). This point coincides with a sharp decrease in new drilling fluid losses to the formation. This permeability decrease does not coincide with any recorded change in the primary lithology as it occurs part of the way though the welded ignimbrite and around PU12 the permeability in appears to increase again.

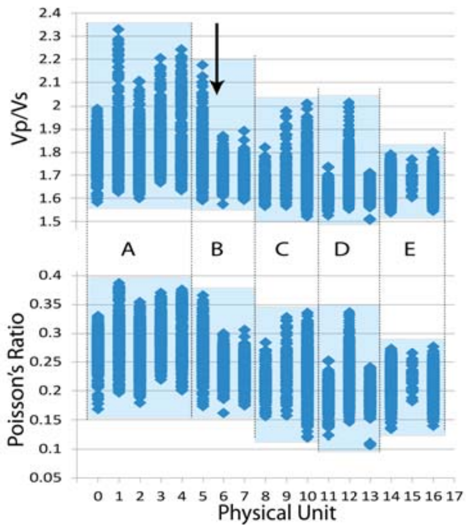

Figure 3. Cross-plots of physical category against Poisson's Ratio (lower plot) and Vp/Vs (upper plot). The blue boxes highlight each lithology. Arrow indicates the point at which drilling fluid losses decreased.

Figure 4 is a cross-plot of Vp against deep resistivity (AI90''), for each PU. PU10 to PU16 plotted in the fast and less conductive sector highlighted by the black ellipse. PU4 and some of PU3 (orange ellipse) is distinctly more conductive and has slower Vp wave velocities than other physical units. However, when PU contact refinements are applied (c.f., R2 in Figure 2) this ellipse highlights only PU4. The remaining categories (PU5-7 and PU9) plot across the range highlighted by the red ellipse. The lower part of the log (below R5) did not plot in a significantly different sector when compare to the other PU's below 1500 m perhaps indicating a change in mineralogy without a significant change in resistivity or Vp.

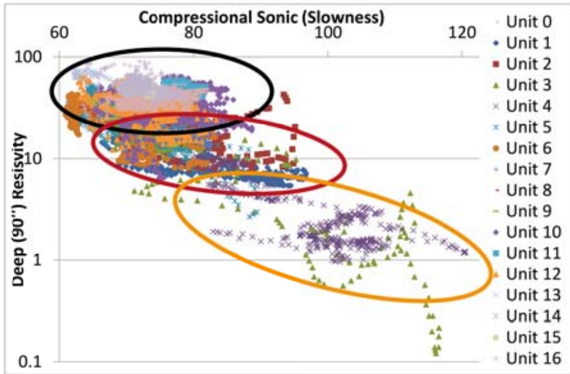

Figure 4. Cross-plot of deep resistivity and Vp with symbology representing physical categories 0 to 16. Black, red and orange ellipses highlight parts of this plot where sufficient different rock properties have separated the data points (refer to text for more detail).

4 DISCUSSION

The Ngatamariki wireline program has, to date, consisted of successfully collecting logs in two injection wells – the first of which is reported here. This paper has outlined early analyses where some simple comparisons have been made between wireline log responses and geologic logs of drill cuttings. Although simple, this kind of work is fundamental to understanding wireline log responses and later applying them to problems such as inferring geology where there has been no drill cutting returned to surface. Beyond stratigraphic refinement and improving our understanding of the geology and alteration, the possible application of wireline data is wide and includes refining conceptual models of permeability, determining physical rock properties, evaluating fractures, characterizing the stress field and calibrating surface geophysical surveys.

4.1 Stratigraphic Refinement of the Ngatamariki Geothermal Field

Depth Correcting Cuttings Logs

Wireline logs are particularly valuable for depth correcting geologic logs made from drill cuttings or core. Calculations of lag times while drilling (i.e., the time it takes for a cutting to travel from the bit face to surface) relies on an understanding of the well hydraulics, cutting size and the lifting capacity of the fluid – where the latter is most dependent on viscosity. Variation in the size, density and shape of the cuttings will impact the cuttings mixing in the wellbore. Fluctuations in drilling fluid viscosity, as is common in well sections drilled with water punctuated with high viscosity sweeps for hole cleaning, will also result in variable return rates of cuttings to surface. These factors reduce confidence that a sample collected at surface represent a particular bit depth.

Seven contact refinements have been identified here (Figure 2: R1-7) with most changes in contact depth being around 10-30 m. In MRP's 3D geologic models a minimum of 50 m stratigraphic offset must occur between wells before the placement of an inferred fault is considered. Close refinement of stratigraphy and the identification of stratigraphic marker horizons within formations will allow us to construct more confident geologic and structural models. We have no doubt that a number of smaller contact refinements will be made from these logs as our understanding of log responses at Ngatamariki improves though acquisition of more logs and further analyses of the present data set.

Inferring Geology and Alteration in Loss Zones

In the interval presented here there were relatively good cuttings returns to surface. However, as production sections of geothermal wells are commonly drilled with water (underbalanced) and will usually encounter sufficient permeability to result in total loss of drilling fluid to the formation with no drill cuttings bought to surface. In the absence of cuttings, wireline logs will allow us to place contacts in the geologic sequence. As our understanding of the log responses in each formation type improves, we will also be able to infer which kind of rock was logged and perhaps even the type and extent of hydrothermal alteration.

Constructing marker horizons in the Tahorakuri

The Tahorakuri Formation is laterally extensive across the Ngatamariki reservoir and hosts the production horizon in the central part of the field. In NM8 it has been separated into seven different lithologies (Lewis et al. 2012), five of which were captured by the wireline logs presented here. Correlating lithologies in a pyroclastic sequence is challenging, particularly in the face of often poor cuttings returns to surface and the complexity of this kind of geologic sequence. Identifying and providing accurate depth control for correlatable marker horizons would significantly improve the confidence of 3D geologic and structural modeling at Ngatamariki. Construction of geophysical marker horizons has been undertaken in geothermal fields internationally. For instance, at Mak-Ban, gamma-ray logs have been used to identify two correlatable permeable horizons consisting of spherulitic rhyolite which have relatively high GR response (Vicedo et al. 2008). In Iceland, rare rhyolite occurrences in the dominantly basaltic reservoir stratigraphy are used as geophysical stratigraphic marker horizons (Danielsen 2010) most likely because they emit more GR than basalts.

Bulk density is commonly used as a measure of the degree of welding in ignimbrites and density is easily measured directly with a formation density log or inferred from sonic velocity data. However, it is problematic to use degree of welding in a chronostratigraphic reconstruction because there is a significant amount of lateral variation both in degree of welding and unit thickness in a single ignimbrite (Wilson and Hildreth 2003). It follows that stratigraphic correlation in a pyroclastic sequence could perhaps be undertaken using repeating sequences, with not too much regard of their thickness, and laterally extensive marker horizons, such as paleosols and ash units. Once marker horizons are identified and correlated they will be used in 3D geologic and structural modeling of the Ngatamariki reservoir.

In NM8 the distinctive response of PU5 (grading sonic velocities and AI with consistent GR) is a possible marker candidate. As is the base of PU12 (1755-1765m) which, with its low GR response, may either be an ash unit (with no alkali feldspars and little clay alteration) or a highly quartz/pyrite veined unit. Close spacing XRD and thin section analysis, or perhaps some other kind of quantitative mineralogy study (e.g., spectral gamma), may help resolve the geologic reasons for log responses, and therefore assist with the creation of correlatable markers. Repeating logs in other wells is also critical, as without the logs no correlation can be undertaken.

4.2 Other Wireline Log Applications

The following outlines some of the applications discussed, adopted or discarded in the interpretation of logs to date. They are not intended to represent the gambit of possible applications, but instead to serve as a sampler of possible applications for logs collected at Ngatamariki and other analogous systems.

Refining Conceptual Models of Permeability

PTS is the indispensable and commonly deployed wireline tool for measuring permeability in a geothermal well. However, alone this tool cannot tell us if the permeability is hosted in fractures, formation contacts, primary porosity, breccias etc. An understanding of how permeability is hosted can be used in optimizing future well targeting activities, informing the numerical modeling of heat and mass transfer in the fields and guiding well stimulation activities. Comparing PTS logs with geologic data derived from drill cuttings or core will go some way to fill this information gap. However, as already discussed above, this material is commonly absent or has poor depth control. Through more accurate mapping of the geologic sequence and comparing this sequence with established permeability indicators (PTS) we will more accurately constrain conceptual models of reservoir permeability.

Deriving Rock Properties from Wireline Logging Data

Wireline logs can provide us a number of rock properties which may in turn be used in geomechanical and numerical models of geothermal reservoirs, or as part of drilling optimization studies. Rock properties may be derived directly from wireline log responses (e.g., density and porosity) or by inversion using either fixed physical relationships or empirical ones (e.g., elastic moduli and compressive rock strength respectively; Chang et al. 2006, Zoback 2007). The latter poses a particular problem for those of us working in an environment dominated by silicic volcanism because there is a paucity of published empirical relationships for this kind of rock.

Fracture Evaluation beyond the Borehole Wall

Hornby et al. (1989) proposed a method for detecting horizontal and inclined fractures, and determining their apparent aperture, using reflected Stonely wave (tube wave) arrivals detected with a dipole sonic receiver. More recently Vp and Vs wave arrival anisotropy has become a tool commonly applied to fracture analysis. Using sonic waves to investigate fracture orientations and apertures is desirable to those of us modeling fractures because it adds another dimension to the more commonly used acoustic or electrical images, which only map borehole wall or a few cm beyond respectively. We suspect that that drilling process results in significant enhancement of fracture apertures at the borehole wall though both unloading and thermal contraction, and that the aperture of fractures at the borehole wall is therefore unlikely to represent true reservoir hydraulic apertures.

Nicoletis et al. (1990) showed that tube wave velocity can be significantly reduced by local borehole damage. Stoneley wave arrivals were recorded in NM8 and we found that chevrons in this wave data are coincident with sharp oversizing in the borehole mapped by mechanical caliper. However in competent formation, plucking of fragments from the borehole wall is more likely to occur where fractures intercept the borehole wall. It follows that the Stoneley wave arrivals are in a way indirectly mapping the fracture occurrences, but are unlikely to be a reliable tool for aperture estimates.

4.3 Wireline Logs as Calibration for Surface Geophysics

Wireline log responses are commonly used in the petroleum industry to calibrate models constructed from geophysical surveys taken at surface (e.g., seismic reflection surveys calibrated using sonic velocity logs and log corrected bed boundaries). To date, we see two key areas of application for wireline logs to surface geophysics in conventional geothermal. First, is quantifying the large scale effects on resistivity in geothermal environments, beyond the well-established low resistivity, smectitie clay response, along with better understanding the resolution of magnetotellurics data and inversions. Second, is applying sonic date to refining velocity models so as to more accurately locate seismicity. The former is described below and the latter is yet to be addressed.

Magnetotellurics and Log Resistivity

Magnetotellurics (MT) has been proven an effective tool for characterizing geothermal resources at the exploration, development and exploitation phase of projects (e.g., Sewell et al. 2012). The correlation between low resistivity and elevated smectite content within an impermeable clay-cap overlying a more permeable reservoir is well established. However, MT imaging below the clay-cap (typically >1000m depth) is not as well understood for a number of reasons including (1) inherent difficulty of resolving features below conductors using EM techniques, (2) poor data quality, (3) poor understanding of the resolution of inversion techniques at these depths and (4) poor understanding of the effects of the conduction mechanisms below the clay-cap which is due to the interplay between bulk rock composition, alteration mineralogy effects, porosity effects, temperature etc. It follows that obtaining downhole resistivity logs offers one way of improving our understanding of what controls resistivity in a geothermal system below the clay-cap.

A comparison of measured downhole resistivity from the NM8 logs with 1D and 3D MT resistivity inversions near this well illustrates the potential utility of obtaining resistivity logs to add to our understanding of resistivity in geothermal fields (Figure 5). This figure shows that above approximately 400m the correlation between resistivity and smectite content is clear. Particularly low resistivities (1-2 ohm.m) are apparent over the 0-200m depth interval coincident with the high levels of smectite within dominantly hosted in the relatively impermeable Huka Falls Formation. Higher resistivities are apparent within the more permeable, lower smectite content, rhyolites and unaltered tuffs and sediments of the Waiora Formation between approximately 200-400m. The 1D TE mode inversion detects this higher resistivity layer better than the 1D invariant and 3D inversions, thus highlighting the importance of utilizing several inversion approaches to obtain the most information.

Below approximately 400m the resistivity interpretation is less clear. In general, both the MT inversions and NM8 AI 90'' show a gradually increasing resistivity with depth. Both the 1D TE mode and 3D inversion show a good match the AI 90'' log. The match between the 1D invariant inversion and this wireline log is not as good due to the non-1D nature of resistivity below 400 m. Lewis et al. (2012) report that the transition from smectite to illite in NM8 occurs at around 700-800m depth. It is likely that above 700-800 m smectite is the dominant cause of low resistivity observed in the MT inversions (generally <5 ohm.m) whereas below this level illite and chlorite are the dominant clays present. It is likely that clays play a role in the observed resistivities. However our comparison between the AI 90'' log, geology and alteration, it is apparent that other conduction mechanisms, such as pyrite and porosity, play a role below 800 m. Although illite and chlorite have much lower cation exchange capacities then smectite, both clays have been shown to lower resistivities in geothermally altered rocks (e.g., Ussher et al. 2000, Flovenz et al. 2005). The effect of porosity on resistivity is well known, and the increasing resistivity with depth in the NM8 AI log is likely due in part to decreasing porosity related either to compaction, the extent of ignimbrite welding or increased secondary mineralization filling pore spaces. The presence of relatively large amounts of quartz-pyrite veining in the phyllically altered, Tahorakuri Formation may also act to lower resistivity.

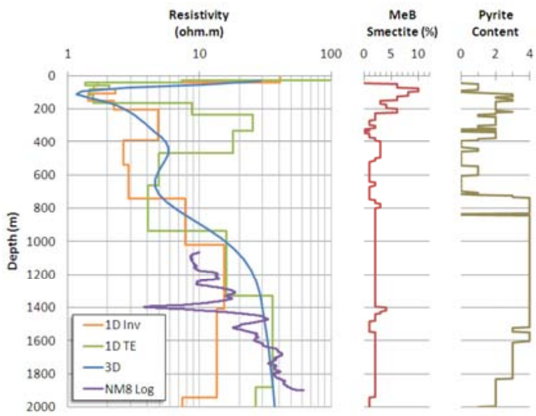

Figure 5. MT inversions plotted (3D, 1D TE mode and 1D) against a smoothed version (running average over ~10m depth intervals) of the 90" AI log (purple line). Pyrite content was estimated in from cuttings under binocular microscope and smectite percentage was determined using methylene blue analysis (Lewis et al. 2012).

The relative importance of each conduction mechanisms in lowering the resistivity will be the subject of further investigation, and logs collected during the Ngatamariki development will be applied to improving understanding of deeper resistivity patterns in MT.

5 CONCLUSIONS

The Ngatamariki logging program which is currently underway demonstrates the utility of wireline logs to problems relevant to a geothermal development – stratigraphic correction and correlation, permeability mapping and targeting, quantifying rock properties for input into models, and calibrating our key geophysical tools.

- Electric wireline logs will respond to lithologic variation in a phyllic altered pyroclastic sequence. Furthermore, they are sensitive to variation in secondary mineralisation. It follows that wireline logs can be used to (1) improve the accuracy of stratigraphic well logs, (2) make inferences about well stratigraphy when no rock cuttings were returned to surface during drilling, and (3) develop stratigraphically correlatable marker horizons with good depth control.
- Rock properties, for use in geomechanical modelling, reservoir modelling and drilling optimisation studies, can be measured directly using wireline logs or derived from logs using direct or empirical relationships. Few empirical relationships have been found for silicic volcanic rocks so further work is required to build these relationships.
- Improving depth control for the stratigraphic sequence in a well will allow us to compare these data with PTS and subsequently refine our conceptual models of permeability. With further work, log responses to secondary mineralisation may prove to be valuable predicative tools for mapping permeable zones.
- The interpretation of magnetotellurics, a key tool in geothermal exploration and development, can be improved through comparison with wireline log responses, particularly array induction, when we are able to constrain the geologic reasons for those log responses.

ACKNOWLEDGEMENTS

The authors would like to acknowledge MRP and Tauhara North No2 Trust for allowing the publication of these data; MRP staff who have supported this logging program; Bill Cumming for moral support, discussion and interpretation; Schlumberger wireline division, particularly Edwin Galeos (NZ Wireline Country Manager) & Ashish Datey (APG East Petrophysics Domain Champion), for advice and working to overcome operational challenges; Geomechanics International for providing program advice; and finally, the Western Energy Services team & the Tyr rig on-site staff for their operational support throughout.

REFERENCES

Boseley, C., W. Cumming, L. Urzua-Monsalve, T. Powell & M. A. Grant. 2010. A resource conceptual model for the Ngatamariki Geothermal Field based on recent exportation well drilling and 3D MT resistivity imaging. In *Proceedings World Geothermal Congress*. Bali, Indonesia.

Chamberfort, I. & G. Bignall. 2011. Petrographic Review of Stratigraphic Units of the Ngatamariki Geothermal Field. In *GNS Science Consultancy Report CR2011/298*.

Chang, C., M. D. Zoback & A. Khaksar (2006) Empirical relationships between rock strength and physical properties of sedimentary rocks. *Journal of Petroleum Science and Engineering,* 51**,** 223-237.

Christenson, B. W., C. P. Wood & G. Arehart (1998) Shallow magmatic degassing: Processes and PTX constraints for paleo-fluids associated with the Ngatamariki diorite intrusion, New Zealand. *Water-Rock Interaction,* ISBN 90 5410942 4.

Danielsen, P. E. 2010. Servicing Geothermal Wells During Completion and Follow-Up Monitoring In *World Geothermal Congress*.

Flovenz, O. G., E. Spangenberg, J. Kulenkampff, K. Arnason, R. Karlsdottir & E. Huenges. 2005. The role of electrical interface conduction in geothermal exploration. In *Proceedings World Geothermal Congress* Antalya, Turkey.

Gercek, H. (2007) Poisson's ratio values for rocks. *International Journal of Rock Mechanics & Mining Sciences,* 44**,** 1-13.

Hornby, B. E., D. L. Johnson, K. W. Winkler & R. A. Plumb (1989) Fracture evaluation using reflected Stoneley-wave arrivals. *Geophysics,* 54**,** 1274-1288.

Lewis, B., I. Chamberfort & A. J. Rae. 2012. Geology of the Injection Well NM8-NM8A, Ngatamariki Geothermal Field. In *GNS Science Consultancy Report 2012/188*.

McLean, K. & D. McNamara. 2010. Fractures interpreted from acoustic formation imaging technology: correlation to permeability. In *Thirty-Sixth Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford.

Nicoletis, L. M. A., A. Bamberger, J. A. Quibleir, P. Joly & M. Kern (1990) Hole geometry and anistropy effects on tube wave propogation: a quasi static study. *Geophysics,* 55**,** 167-175.

Sanyal, S. K., M. Che, R. E. Dunlap & M. K. Twichell. 1982. Qualitative Response Patterns on Geophysical Well Logs from The Geysers, California In *Geothermal Resources Council Transactions*.

Serra, O. 1990. *Element Mineral Rock Catalog*. Schlumberger.

Sewell, S., W. Cumming, L. Azwar & C. Bardsley. 2012. 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. In *Workshop on Geothermal Reservoir Engineering*. Stanford, California.

Stefansson, V., S. T. Gudlaugsson & A. Gudmundsson. 2000. Silica Content and Gamma Ray Logs in Volcanic Rocks In *World Geothermal Congress*.

Stimac, J. A., M. Baroek, A. Suminar & B. Sagala. 2010. Integration of surface and well data to determine structural controls on permeability at Salak (Awibengkok), Indonesia. In *Proceedings World Goethermal Congress* Bali, Indonesia.

Ussher, G., C. Harvey, R. Johnstone & E. Anderson. 2000. Understanding the resistivities observed in geothermal systems. In *Proceedings World Geothermal Congress*. Kyushu-Tohoku, Japan.

Vicedo, R. O., J. A. Stimac, V. T. Capuno & J. B. Lowenstern (2008) Establishing major permeability controls in the Mak-Ban Geothermal Field, Philippines. *GRC Transactions,* 32**,** 309-313.

Wallis, I. C., D. McNamara, J. V. Rowland & C. Massiot. 2012. The nature of fracture permeability in the Basement Greywacke at Kawerau Geothermal Field, New Zealand. In *Proceedings, Thirty-Seventh Workshop on Geothermal Reservior Engineering*, SGP-TR-194. Stanford University, Stanford, California.

Wilson, C. J. N. & W. Hildreth (2003) Assembling and ignimbrite: mechanical and thermal building blocks in the Bishop Tuff, California. *The Journal of Geology,* 111**,** 653-670.

Zoback, M. D. 2007. *Reservoir Geomechanics*. Cambridge: Cambridge University Press.