CHARACTERIZING FEED ZONES IN GEOTHERMAL FIELDS: INTEGRATED LEARNINGS FROM COMPLETION TESTING, IMAGE LOGS AND CONTINUOUS CORE

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Keywords: *Geothermal, feed zones, permeability, image logs, continuous core, Wairakei, Tauhara, well targeting*

1. ABSTRACT

The Wairakei and Tauhara geothermal fields lie within the Taupo Volcanic Zone in the North Island of New Zealand. Both fields are currently utilised by Contact Energy Ltd for electricity generation, which began in the 1950s. There is a resulting wealth of information in the form of completion testing data including pressure, temperature and fluid velocity profiles, referred to here as PTS data. PTS data have traditionally constituted the primary source data used for interpretation of feed zones. More recently, the interpretation and understanding of feed zones has been enriched by combining PTS data with acoustic formation imaging logs or continuous core. Integrating these datasets refines the understanding of the distribution and nature of feed zones which are the ultimate target for both production and injection wells.

2. INTRODUCTION

Contact Energy Ltd operates the Wairakei and Tauhara geothermal fields which lie on the southern end of the Taupo Volcanic Zone in the North Island of New Zealand (Figure 1). Crucial to the successful utilization of a geothermal system is the knowledge of the permeability structure, and specifically 'feed zones' which are the sources of geothermal fluid entry into the wellbore. Understanding the nature and distribution of feed zones is particularly relevant for well targeting and useful in providing constraints to reservoir models.

Feed zones are an indication of permeable zones in a well, but it should be noted that not all permeable zones will show as feed zones during a PTS run. The distinction between a permeable zone and a feed zone is that a feed zone requires interconnected permeability *and* a pressure difference with respect to the fluid column in the wellbore at the time. If the fluid pressure in the feed zone is greater than the fluid column at this depth, then the fluid will enter the well. Similarly, if the fluid pressure in the feed zone is under-pressured, then fluid will escape the well into the formation. This is a dynamic process, and flow regimes at the permeable zones can make the feed zones 'appear' and 'disappear' as conditions change.

Understanding of feed zones is achieved by different methods. Feed zone locations in the wellbore are initially located during a 'completion test' with a temperature-pressure-spinner (PTS) probe.

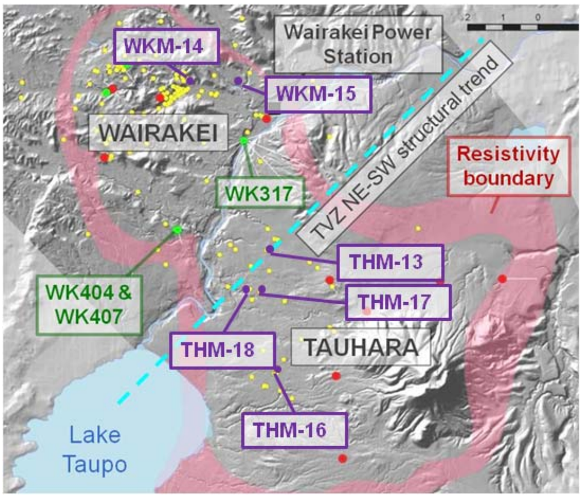

Figure 1: Map of Wairakei-Tauhara showing wells discussed in this paper (modified from McLean, 2011)

In 2008-2009, Contact Energy led an extensive geothermal subsidence investigation involving some 4.5km of high-quality continuous core from 13 boreholes up to 800m deep drilled in the Wairakei and Tauhara geothermal fields. Further information is found in Bromley et al, 2009; Brockbank et al, 2011; and Ramsay et al, 2011. Attempts were made to find correlations between rock parameters measured in the core and feed zones (Glynn-Morris et al, 2010). As continuous core is available to ~800m, the core has assisted in understanding the shallow swelling clay layer and upper reservoir at Wairakei-Tauhara.

Additionally, since 2008, Contact Energy has run acoustic logs in the open-hole sections of several deep production and injection wells at Wairakei-Tauhara to help characterize fracture distribution. As AFIT logs are primarily run below the production casing shoe, they have assisted in understanding the mid and deep reservoir. In this context, correlations between measured fractures and feed zones have been documented at depths greater than 2000 m (McLean et. al, 2011).

This paper reports preliminary findings from integration of PTS, fracture logs and core. Implications for our understanding of permeability in the geothermal reservoir are discussed. The differences encountered between the methods highlight the importance of an integrated approach to study feed zones.

There has been an ongoing debate about the contribution and relative importance of (i) primary, formation and lithological permeability versus (ii) secondary, fracture and tectonic permeability, especially with depth. The aim of this paper is to focus on the permeability component of feed zones and shed further light on the debate.

3. GEOLOGICAL SETTING

The geology of the Wairakei-Tauhara Geothermal system can be simplified as follows: The cap rock (or 'swelling clay layer') to the system is the hydrothermally altered Huka Falls Formation (HFF), in which a Middle HFF unit consisting of permeable pumice breccias is found. Both Upper and Lower HFF are dominated by relatively impermeable lacustrine sandstones and siltstones. The upper reservoir underlies the HFF and is hosted below this in the Waiora formation, a thick (1500-2000m) sequence of ignimbrites with extensive lava (rhyolitic and andesitic) units. The deeper reservoir is in the Whakamaru Group Ignimbrites, Tahorakuri formation, which overlie the Torlesse Greywacke Basement. An extensive summary of the geology is found in Rosenberg et al, 2010.

4. COMPLETION TESTING AND FEED ZONES

4.1. Introduction

Completion tests are performed on most wells immediately after the well has been drilled and the slotted liner landed, while the rig pumps are on-site. A completion test consists of injecting cold water at different pump rates into the well then closing the well and allowing it to heat up.

The main purpose of a completion test is to identify and characterise the feed zones in a well. Some of the ways feed zones can be identified is by fluid loss or gain and temperature changes in the wellbore.

4.2. Methodology

A completion test consists of injecting water into the well and then allowing the well to heat up. Usually three injection rates are used, followed by a pressure fall-off (PFO) test and numerous heating runs. Heating runs are performed immediately after the PFO, typically at intervals of one hour, one day, one week and one month.

At the same time, during injection and heating, a pressure-temperature-spinner (PTS) tool is run up and down in the well, continually measuring these parameters. While simultaneously measuring pressures and temperatures, the spinner is used to measure the fluid velocity and direction in the well. At a given pump rate, changes in fluid velocity measured by the spinner indicate either changes in the cross sectional area of the wellbore or fluid loss or gain.

4.3. Observed correlations

The reservoir engineer generally uses the flowing correlations in the well, measured from the PTS tool, to identify and understand the nature of feed zones:

- Pressure measurements are used to quantify the overall permeability of the well. The pressure increases as a result of an increased water injection rate, therefore the less the pressure increases in relative terms, the greater the bulk permeability of the well.

- Spinner data measures the amount of fluid loss or gain, and therefore, the feed zone size (useful while injecting water or when shut-in to identify internal flows).

- Temperature changes in the well.

Ideally the final pressure and temperature will provide information to characterise the fluid state in the formation at the feed zone, specifically whether it is a steam, two-phase or liquid feed zone.

All of the above correlations are considered collectively to gain an understanding of the overall well permeability and the contribution of each feed zone to this permeability.

4.4. Implications

PTS data will provide a first indication as to the location, size and state (e.g., liquid, steam, etc.) of a feed zone. Further refinements specifically on the nature of the permeability, can be made by considering well conditions. If the signature is diffuse then either (a) the slotted liner does not have sufficient perforations and is 'averaging' the signature, or (b) the permeability is more widespread, and less concentrated. Therefore in the later case, we would expect the feed zone to be either formation permeability or a diffuse interconnected fracture set. If the signature is concentrated, then we can infer either a sharp lithological contact, or a concentrated fracture cluster.

An example of a 'diffuse' feed zone is illustrated in Figure 2. Here the fluid velocity is relatively stable down the well until ~340 m when it starts declining linearly, reaching zero at ~440 m. The temperature during injection at this depth interval is constant at 22 ˚C (which is the temperature of the injected water) and below this depth starts increasing slowly. After one hour heating, the temperature over 340-440 m has increased a constant 20 ˚C and after one month has heated up more.

Contrarily, Figure 3 shows a very sharp feed zone at 110 m. This is shown by the sharp decrease in fluid velocity at this depth and the temperature increases during heating.

The completion test data is usually considered in conjunction with other data collected while drilling, such as stratigraphy and hydrothermal alteration, or post-drilling data, such as well performance while producing or injecting, in addition to information from nearby wells. All data considered together is useful to help refine these interpretations.

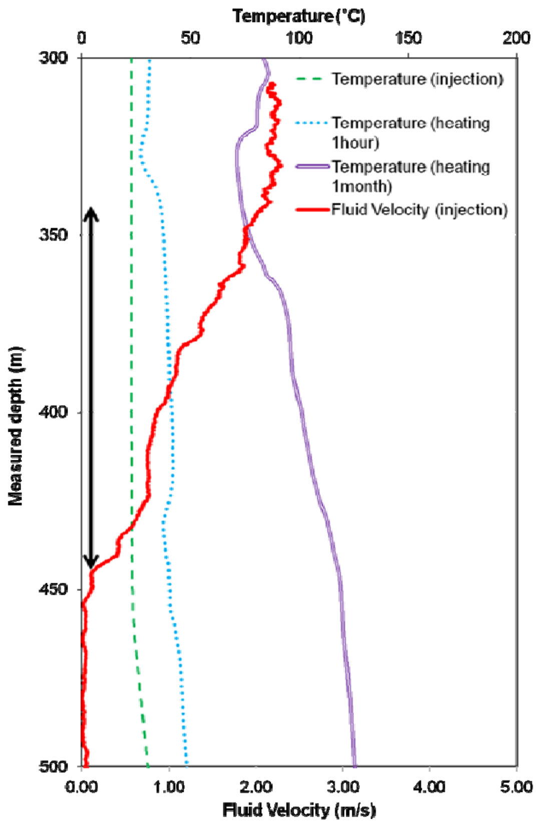

Figure 2: Temperature and fluid velocity profiles showing a diffuse feed zone. The arrow indicates the extent of the feed zone.

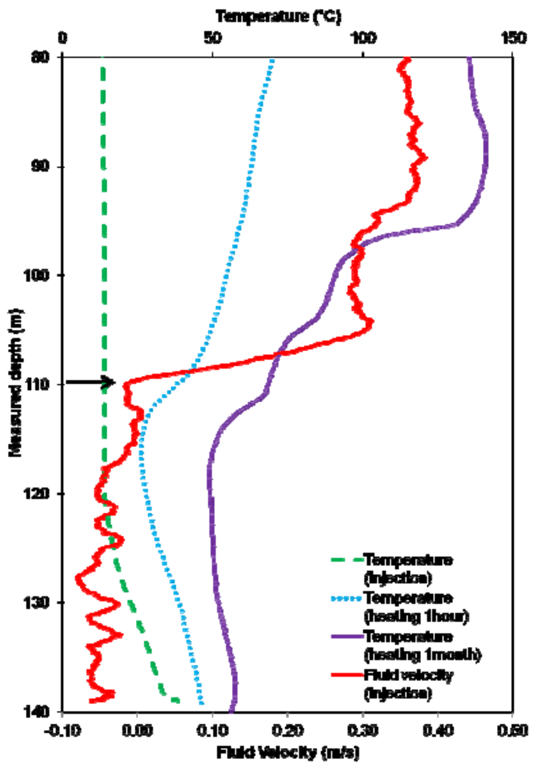

Figure 3: Temperature and fluid velocity profiles showing a sharp feed zone. The arrow indicates the location of the feed zone.

5. CONTINUOUS CORE AND FEED ZONES

5.1. Introduction

In the geothermal energy development, and particularly in developed fields, rotary drilling with a tricone or Polycrystalline Diamond Drag Bit (PDC) are the most common (and economical) drilling methods for a geothermal well. This drilling method brings small rock chips to the surface (called "cuttings") in the circulating drilling fluid. While this is suitable for determining rock type and alteration, structural and bulk rock property data are lost. Contrarily, continuous coring, which provides a 'tube' of intact rock from the well, contains a plethora of additional information available for study.

The subsidence investigation led by Contact Energy in 2008-2009 provided a rare opportunity to obtain extensive continuous core in a producing geothermal field. Glynn-Morris (2010) and Brockbank, (2011) have examined the correlation between feed zone locations determined from completion test data, other measurements from the drilling process such as circulation losses, and the core measurements of physical and material properties. It should be noted that the core was not oriented, and so while fracture dip can be measured, fracture orientation data are not available.

5.2. Methodology

The following factors were considered for the integrated interpretation of PTS data, acoustic logs and core:

(a) Lithological information (distinguishes between permeability within and at lithological contacts)

(b) Rock-Quality Designation (RQD) (an index for rock intactness, which provides a proxy to fracture density)

(c) Recovery Factors from drill core (a proxy to high fractures density and poor material properties; either unconsolidated soil or weak clays)

(d) Fluid loss zones of drilling data (provides an indirect bulk measurement of the open-hole wellbore permeability between the last cemented casing shoe and the drill bit, however it masks permeability below the first total-loss zone)

(e) Porosity (measures void space in intact rock core sample)

(f) Swelling clays (measures primarily smectite clay, generally from the argillic alteration in the cap of a geothermal system)

(g) Rock strength (measured the point force required to break a fragment of core, either along the axis or across it)

(h) Core photos (allows for visual inspection of the core, and helps differentiate between drilling-induced and natural fractures)

5.3. Observed correlations

Four continuously-cored wells at Tauhara were considered in for the Glynn-Morris (2010) study, two shallower wells targeting the Middle Huka Falls formation THM-13 (416m) and THM-17 (294m), and two deeper wells targeting the upper geothermal reservoir in the Waiora formation THM-16 (801m), and THM-18 (717m). In this study, these wells are reviewed in conjunction with two other deeper continuously-cored wells at Wairakei, WKM-14 (616m) and WKM-15 (596m). Results are summarized in Appendix Table 1 below. The Appendix also contains a sample of core photos of feed zones and correlation plots from THM-16 & 18.

(a) Lithological information: The current interpretation for many wells at Wairakei has been that feed zones most often occur at formation contacts, but this is not generally observed in the cored holes. At shallower levels in the shallow swelling clay layer, and at the top of the reservoir, lithological contacts seem to be more important in terms of geological controls on permeability. Particularly within the shallow (~200-300m depth) Middle Huka Falls Formation (pumice breccias) the steam feed zones are found near the top where it is 'trapped' by the Upper Huka Falls Formation, a siltstone which acts as a low permeability barrier to upward migration of steam. In deeper levels within the convective geothermal reservoir, the feed zones seem to occur primarily within formations such as the Waiora or Tahorakuri. Of particular note is the feed zone in the moderately permeable well THM-18, which occurs in the lower-middle of the Spa Andesite lava. This is in apparent contradiction with the core textures showing moderate brecciation within the margins of this unit. With the exception of Spa Andesite, a general observation is that feed zones correlate feed zone with the tops and bottoms of rhyolites, such as the Karapiti 2A or Racetrack Rhyolite (such as TH18), where the permeability is dominantly stratigraphic and created by primary brecciation.

(b) Rock-Quality Designation (RQD): As this is a proxy to fracture density, most substantial feed zones are found at zones of increased local fracturing. However the reverse is not true, as the areas of greatest fracturing do not lead necessarily lead to the existence of feeds. Where the feed is identified using PTS, its location can be refined using RQD.

(c) Recovery Factors from drill core: Generally associated with RQD as increased fracturing leads to greater difficulty recovering the core. As RQD above, feed zones are correlated with localized drops in core recovery.

(d) Fluid loss zones from drilling data: Correlates well, as this is a direct measure of the near-wellbore permeability, if the feed is the first permeable zone out of the shoe and is not masked by the permeable zone above.

(e) Porosity: Feed zones are in the wells that were continuously cored, are not related to high intact-rock porosity but are correlated with average or low porosity, which might reflect the greater tendency to fracturing.

(f) Swelling clays: Most feed zones of interest are below the swelling clay layer, but for the shallow feed zones there is a moderate swelling clay abundance; these feed zones are not found to correlate with an increase or decrease of swelling clay. Based on the common spatial correlation between moderate abundance of swelling clay and HFF, the swelling clay is thought to relate to the inherent clay content of lacustrine sediments from the Upper and Lower HFF units.

(g) Rock strength: Within the same unit such the Middle HFF in THM-13, the top two phase feed zone and bottom liquid feed are correlated to the lowest and highest rock strength in the core recovered in the well. In THM-18, the strongest core is on the middle of the Spa Andesite, and the feed zone occurs below this. Elsewhere the correlation is less clear.

(h) Core photos: View the core directly to refine the interpretation as see what the feed zones look like.

5.4. Implications

The work with the continuous core has provided a unique opportunity to 'see' what feed zones look like (where core recovery is sufficient) as shown in the Appendix.

What is clear is that for shallower high porosity units such as the Middle HFF (30-50%), the feed zones demonstrate formation/primary permeability in a well with a low injectivity index. However, in the same unit, more productive feeds seem to be associated with fracturing in addition to the higher porosity.

In the upper geothermal reservoir Waiora Formation (10-50% porosity), which lies below the HFF, most of the feed zones are correlated with localized fracturing within the unit and not correlated to high porosity. This suggests that even in volcanic deposits with high porosity, fracture permeability seems to be the dominant permeability at feed zones within the upper reservoir. This also suggests that porosity by itself does not account for the degree of connectivity of pore space, which is ultimately relevant for interpretation of feed zones.

Additionally, it seems that in general, the rock strength is lower as the top of the Middle HFF which is characterized by a two-phase steam cap, indicating a weakening of the formation through alteration of the rock matrix to thermal clays. Contrarily, at the base of the unit, the rock strength seems to be higher where the feed zones are liquid, suggesting a strengthening process through the deposition of silica. Further work is required in this area

6. IMAGE LOGGING AND FEED ZONES

6.1. Introduction

The relatively recent introduction of the high-temperature acoustic formation imaging tool (AFIT) allows the use of the technology in wells up to 300ºC. AFIT logs have been taken in a number of wells in both the Wairakei and Tauhara Geothermal Systems, and example is shown in Figure 4 below. The fracture datasets obtained are extensive and are useful in understanding the type of permeability intersected by the wells in these fields.

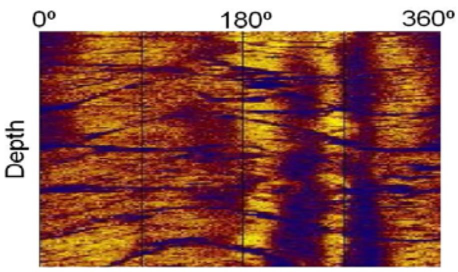

Figure 4: Example of AFIT amplitude response with sinusoidal intersection of fracture plane with wellbore (from Mclean and McNamara, 2011)

6.2. Methodology

During operation, the AFIT tool produces an acoustic signal which is directed from the tool out into the well via an angled mirror. The signal travels through the well fluid and encounters the wall rock where it is attenuated. Some of the signal is reflected back towards the mirror in the tool where it is directed back up towards the receiver. The angled mirror also rotates as the tool moves down the well, producing a helical scan of the wall rock. The time taken for the signal to return to the receiver (the 'travel time') and the 'amplitude' of the returned signal produce two different images of the wall rock. When interpreted together a fracture dataset is produced, including information such as depth, azimuth, dip, width and type (McLean and McNamara, 2011).

6.3. Observed correlations

Of the complete fracture dataset produced by interpretation of the AFIT scan, only some fractures will contribute to fluid flow. This is because not all fractures are open (some are filled with minerals such as clays or calcite) and not all open fractures are extensive or interconnected beyond the wall rock in the well. To identify the fractures which do contribute to fluid flow in the well, the fracture datasets are correlated with feed zones interpreted from completion testing. This has been done for sections of the image for three wells deeper than 2200m (McLean and McNamara, 2011).

While the most obvious correlation would be feed zones where there is high fracture density in the well, it has been found that the fracture density measured by AFIT is too dependent on the variable image quality. However a good correlation is observed between single wide aperture fractures and feed zones. These wide aperture fractures from the image likely represent zones of fracturing or faults underground as shown in Figure 5 below (McLean and McNamara, 2011).

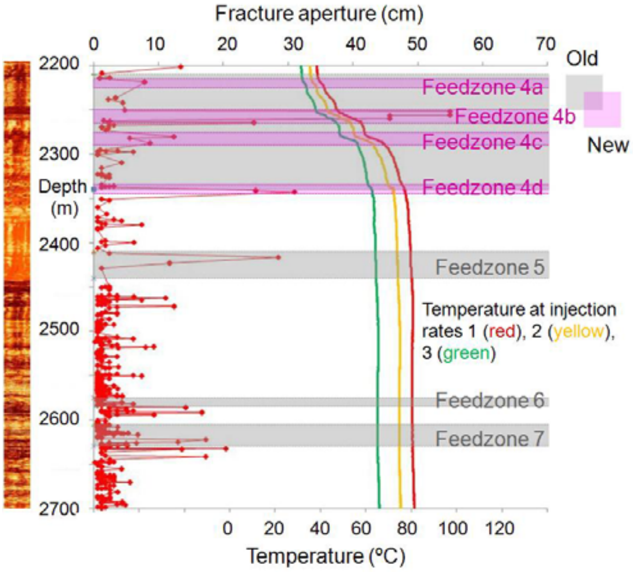

Figure 5: WK404 upper feed zone refinement using fracture aperture and temperature profiles. Old feed zones (grey) are overlain with new feed zones (pink) (from Mclean and McNamara, 2011).

6.4. Implications

In the wells analysed to date the azimuth of the wide-aperture fractures is, with few exceptions, within a few degrees of the maximum horizontal stress known in the area. The maximum horizontal stress is known from vertical tensile fractures and other features seen in the AFIT logs. The implication of this is that the fractures are created and remain open due to the tectonic stress regime. Therefore the permeability identified in these deep wells can be classified as secondary fracture permeability due to tectonic stress (McLean and McNamara, 2011).

7. DISCUSSION

The understanding of feed zones identified through completion tests and heat up surveys has been enhanced through the recent addition of continuous core and AFIT data. The former has allowed for a better understanding of the swelling clay layer and the upper reservoir, the latter has provided insights into the deep reservoir.

Reservoir engineering in the geothermal industry has evolved from experience of the oil and gas industry. The geothermal industry is in a state of continuous improvement, but due the much smaller size of the industry and relatively more challenging drilling conditions resulting in greater technological limitations, the industry still lags behind in its understanding of permeability and specifically its ability to target wells with precision. This is illustrated by a typical oil and gas completion where a plain liner is run, and perforated at several specific targets. By contrast, in geothermal usually a fully perforated liner is installed over most of the well below the production casing shoe, and this length can amount to over a thousand metres.

By studying the nature of permeability with the increasingly growing subset of tools and techniques from the oil and gas industry, perhaps eventually geothermal wells will be completed with a similar level of precision, which ultimately, will result in a better use of the resource.

8. CONCLUSION

With the addition of newer tools and techniques suitable for geothermal downhole conditions, such as formation image logs and high-recovery continuous coring, this study has provided further information and analysis on the nature of feed zones and permeability at Wairakei-Tauhara. In general, our preliminary work suggests that with increasing depth, the importance of (i) primary, formation and lithological permeability decreases and (ii) secondary, fracture and tectonic permeability increases.

Formation permeability is identified by a more diffuse PTS signature within a particular lithological unit (as long as the liner has sufficient perforations). In shallow low permeability wells, feed zones can exist within a permeable unit without fracturing. However, in moderate permeability wells targeting the same unit, feed zones are characterized by some natural fractures within the same permeable unit indicating the added contribution of fracture permeability.

Fracture permeability seems to be the dominant form of permeability at Wairakei-Tauhara, below 1000m depth, and it can be identified by a more concentrated PTS signature. While feed zones correlate well with fracture density, it is not a reliable predictor of the occurrence of feed zones. Steeply dipping fractures, and highly localized fracture density (or bulk fracture aperture) are the best predictors of permeability in a well. These are identifiable by formation imaging in open hole, or through continuous coring.

Future work is required to refine these ideas and could involve:

- A comprehensive study of all the feed zones of the Wairakei-Tauhara and Ohaaki field
- A study on the effect of the perforated liner on the PTS signature by comparing completion test data before and after running the liner
- Combining AFIT logs and continuous core over the same interval with a feed zone

9. ACKNOWLEDGEMENTS

The authors express their appreciating to Contact Energy for allowing the data to be presented. Particular thanks to Paul Bixley and Fabian Selpulveda for their guidance and ideas.

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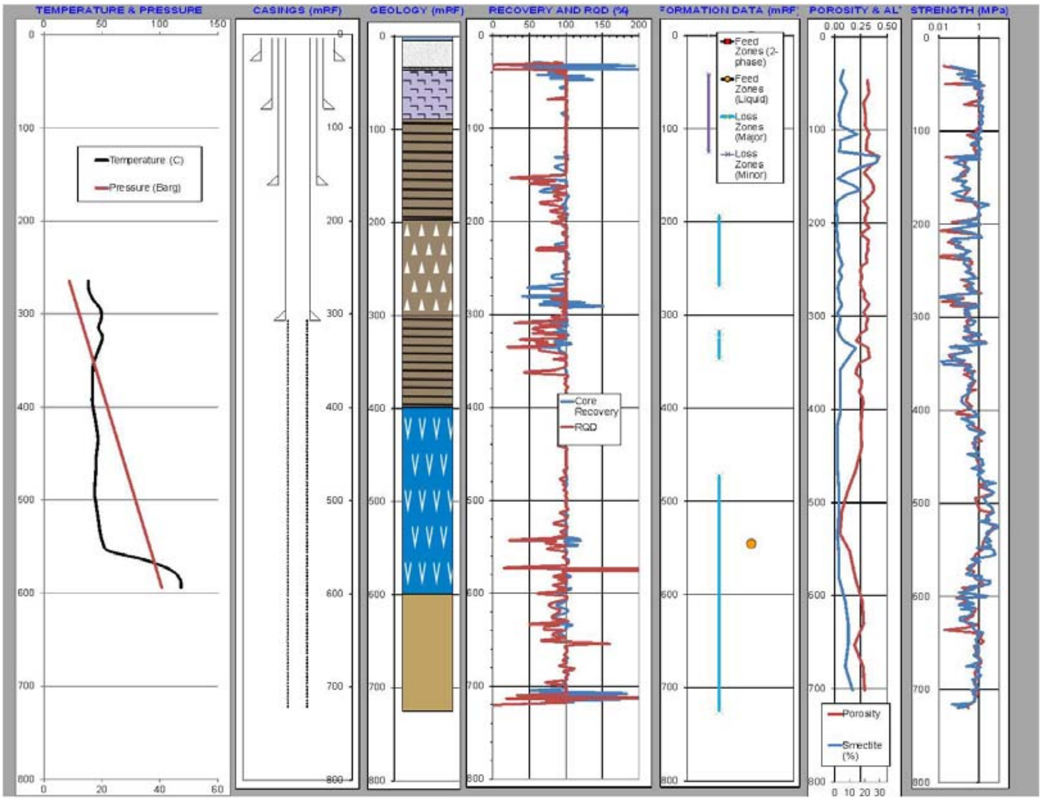
11. APPENDIX

Characteristic	THM-13	THM-17	THM-18	THM-16	WKM-14	WKM-15	Comments
RQD	100%	50% (upper) 75% (lower)	25%	95% (upper), 25% (lower)	100% (upper) 25% (lower)	25-75% near top and bottom	Major feedzones mostly correlated to fractures
Recovery	100%	50% (upper) 95% (lower)	75%	95% (upper) 25% (lower)	100% in both	90% near top and bottom	Major feedzones mostly correlated to fractures
Rock type	MHFF (mid)	MHFF (top & bottom)	Spa Andesite (bottom)	Waiora (mid)	Waiora (mid)	Waiora (mid)	Not necessarily at boundaries
Fluid loses	Major Loss	Major Loss	Major Loss	Major Loss	Major Loss	Major Loss	Well correlated to drilling losses
Porosity	Average porosity	Lowest porosity	Low porosity	Average porosity	Average to low porosity	Average porosity	Not related to high porosity.
Rock Strength	Moderate	Lowest and Highest	Moderate	Strong	Moderate	Moderate	Feeds sometimes at high/low
Swelling clays	Moderate	Moderate	Low	NA	Low	Low	Below conductor
Injectivity Index (t/h/bar)	3	7	11	> 100*	28	17	Indicates bulk permeability

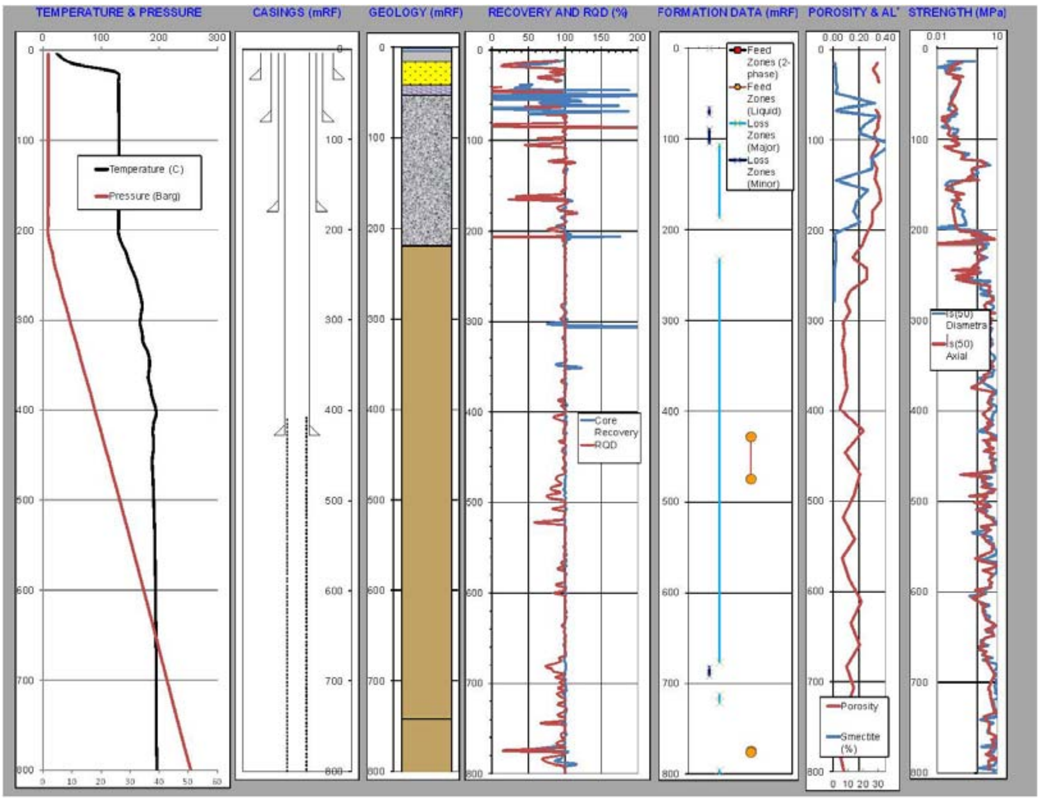
Table 1: Correlations between feed zones and parameters encountered from continuously cored wells. Injectivity index from Bromley et al., 2010. *Injectivity not representative due to strong internal flow when completion test performed.

Appendix Figure A: Core photos from THM-18, showing feed zone in Spa Andesite

Appendix Figure B: Core photos from THM-16, showing feed zone in Waiora Formation.



Appendix Figure C: Graphs of THM-18 data comparing feed zone characteristics obtained from the completion test data to measurements obtained from drilling data and coring measurements



Appendix Figure D: Graphs of THM-16 data comparing feed zone characteristics obtained from the completion test data to measurements obtained from drilling data and coring measurements