Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Comparing Borehole Televiewer Logs with Continuous Core: An Example from New Zealand

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Keywords: BHTV, geothermal, acoustic borehole imaging, wireline log, continuous core, fracture analysis, AFIT

1 ABSTRACT

The use of borehole televiewer logging is a recent addition to the well logging toolkit available to the geothermal industry in New Zealand. The information acquired from borehole televiewer (BHTV) equipment, such as the Acoustic Formation Imaging Technology (AFIT) tool provides valuable geological information about the geothermal reservoir. This paper investigates the accuracy of acoustic borehole imaging in a geothermal environment by comparing the information from a continuous core to a BHTV log acquired using the AFIT LT tool. This study is unique in the New Zealand geothermal industry as the data presented here has been obtained from the only well to have both a borehole image and continuous core over the imaged well interval.

2 INTRODUCTION

Geological information on the subsurface of geothermal reservoirs of the Taupo Volcanic Zone (TVZ) is often limited to descriptions of drill-cuttings and spot-coring. These techniques themselves are sometimes subject to poor recovery rates of drill-core, drill-cuttings mixing within the wells, and incomplete cuttings returns (Massiot et al., 2014; Wood, 1996). As such, information on lithological heterogeneity, texture, and layering, as well characterisation of structural networks of these rocks, can be limited. Intermittent geological outcrop exposure and limitations of seismic surveys also contribute to this information gap (Hunt et al. 2009). The recent advent of borehole televiewer (BHTV) logging to the geothermal industry toolkit in New Zealand has provided a new source of potential information on subsurface geology and structure.

BHTV tools use a rotating transducer (or a stationary transducer and a rotating mirror) to a) transmit sonic pulses to the borehole wall, where they are attenuated by the formation, natural and induced structures, and b) receive any returning sonic signal. Two types of information are recorded by BHTVs (Zemanek, et al., 1970); the sonic wave travel time (providing information on borehole shape), and sonic wave amplitude (providing information on the acoustic impedance of the formation). BHTV tools use this data to create oriented, 360° images of the inside of a well, which can provide data on lithology, structural features such as fractures and faults (orientation, width, fill), and *in-situ* horizontal stress orientations (from induced features). Geothermal BHTV logging first became available in New Zealand in 2009 with the introduction of a high temperature (≤300°C) BHTV tool (Acoustic Borehole Imager ABI85-92) developed by Advanced Logic Technology Ltd. This equipment is deployed commercially as the Acoustic Formation Imaging Technology (AFIT) tool by Tiger Energy Services Ltd. Two types of tool are available; the high temperature capable AFIT tool (AFIT HT), and a lower temperature range, slim-hole (43mm diameter) AFIT tool (AFIT LT) (Table 1). To date Contact Energy has used both these tools to image 14 geothermal wells.

The data from these images are some of the first direct observations of subsurface lithological and structural characteristics of the hydrothermally altered, pyroclastic, volcanic, and volcaniclastic formations that make up many of New Zealand's geothermal reservoirs. These BHTV logs have been utilised to refine lithological boundaries, characterise structural networks and *in-situ* stress fields, and refine the locations of fluid zones and characterise the nature of their permeability (McLean and McNamara, 2011; Wallis et al., 2012; Massiot et al., 2013; McNamara et al., in prep).

Table 1: Specifications of the AFIT HT and AFIT LT BHTV tools (Tiger, 2014).

	AFIT HT	AFIT LT
Temperature Limit (°C)	300	135
Tool Diameter (mm)	85	43
Pressure Limit (bars)	800	800
Tool Length (m)	5.21	2
Tool Weight (kg)	150	10
Vertical Resolution (mm)	4	4
Logging Speed (m/sec)	2-20	2-20

This paper investigates the accuracy of BHTV logging in a New Zealand geothermal environment by comparing a continuously cored well to a BHTV log acquired using the AFIT LT tool. In the context of this paper, 'accuracy' is defined as how well the BHTV log captures and reproduces the information from the drill-core. The accuracy of BHTV logging can be variable subject to borehole image quality and coverage, which can be affected by borehole irregularity, the behaviour of the sonic wave in well fluids at geothermal temperatures and pressures, the orientation of geological features relative to the orientation of the well, and also by the nature of the geothermal lithologies themselves. Some of these technique-limiting factors have been addressed through statistical and empirical methods (Massiot et al., 2014; Massiot et al., 2012). A positive match between features displayed by BHTV logs and drill-core information can be extremely valuable to refine the interpretations of BHTV logs.

This will provide a comparative example and assessment on the accuracy, volume and type of data that can achieved from BHTV logging in New Zealand geothermal wells. This work is unique in the New Zealand geothermal industry as the dataset presented here is one of a kind in that it is the only well to have both a borehole image and continuous core over the same depth interval.

3 DATA

3.1 Coring and BHTV Log Acquisition

The drill-core obtained is approximately 630m long and passes through a sequence of welded and non-welded ignimbrites, volcaniclastic sediments, tuffs and lavas. The drill-core was obtained using HQ triple tube core barrel to continuously core the well, with a 98% recovery rate. The drill-core was manually logged for lithology and fracture information (including mineral fill, fracture type, aperture etc.), and high resolution photographs and a core trace were taken. The 116m BHTV log was acquired predominantly through a weak to moderately hydrothermally altered ignimbrite with variable welding. Data acquisition was performed by Tiger Energy Services (TES) using the AFIT LT tool. Due to this tools temperature limit of 150°C only 116m of acoustic image was acquired as going deeper would have exceeded the tools operating capability. The log was collected in 4 separate logging runs. During acquisition the tool remained centralised and experienced high signal return from the borehole wall.

3.2 BHTV Log Processing

BHTV logs were analysed using RECALL 5.4™ and WellCad software. Image features are classified using the Massiot et al. (2014) system for TVZ, geothermal, acoustic images. Fracture apertures are measured directly from the acoustic image and scaled to the average diameter of the borehole (3.875 inches/ 98.5 mm) and as such are only approximations. Although apparent aperture can be proportional to the true aperture of a fracture it does not directly correspond to the hydraulic aperture as many other physical properties can influence the acoustic impedance contrasts associated with a structure (Cheung, 1999; Valley, 2007; Davatzes and Hickman, 2010). As such apparent aperture measurements presented here are most likely over-estimates (Davatzes and Hickman, 2005).

3.3 BHTV Log Analysis

On acoustic images, planar features such as fractures and bedding, are shown as sinusoids (Figure 1). The same is true of traces of the drill-core (Figure 2, Figure 4, Figure 5). Drill-core traces and photographs were loaded into the RECALL 5.4™ software and correlated to the acoustic image based first on recorded depths. Then drill-core traces and photographs were depth shifted to match features on the acoustic image. Once depth matching was finished the drill-core traces and photographs were rotated so that sinusoid orientation and morphology on the trace matched that of the corresponding feature on the acoustic image.

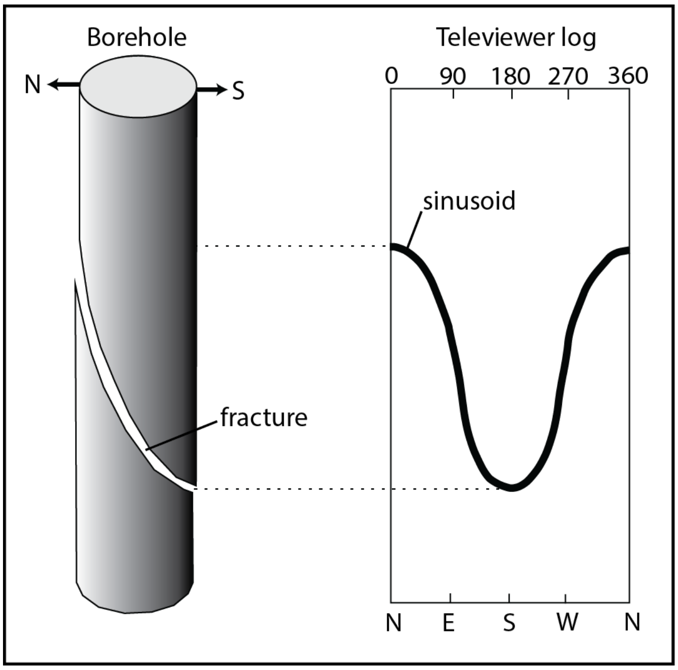

Figure 1: Schematic of how a planar feature (e.g. fracture) in a borehole appears on a BHTV log.

3.4 Image quality

The coring process produced a smooth, cylindrical borehole, as evident from 3-D projections of the borehole from BHTV travel time data. This contributed to the generation of an overall high quality acoustic borehole image, in which 2% of the image was interpreted to have 'bad' image quality (0% of the image was available for interpretation), 19% 'poor' image quality (<50% of the image was available for interpretation), 40% 'moderate' (between 50% and 75% of the image was available for interpretation) and 39% 'good' (>75% of the image was available for interpretation). 'Bad' image quality is attributed to casing effects on the tool sensors at the top of the image, and 'poor' image quality is due to image artefacts, such as 'stick and pull' (Figure 2) and stabilizer marks (Lofts and Burke, 1999).

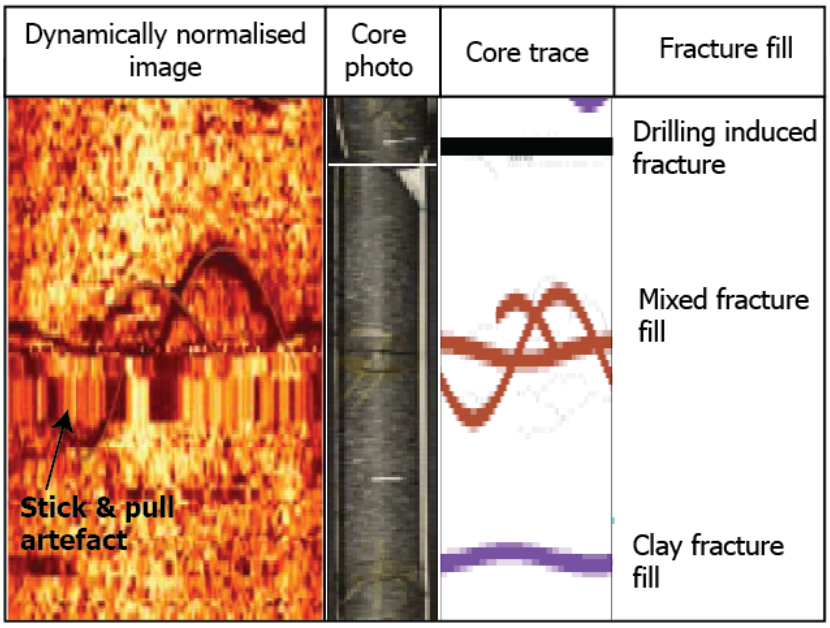

Figure 2: Diagram showing, over the same depth interval, a dynamically normalised acoustic image containing a stick & pull artefact, core photograph, orientated core trace, and type of fracture.

4 RESULTS

4.1 Fracture Identification

A total of 377 fractures were identified on the BHTV log, 351 of which are of geological origin. Twenty-six of these fractures are drilling induced features, known as drilling induced tensile fractures (DITFs), which will be disregarded as they form on the borehole wall after the passage of the drill bit, and hence will not be present on the drill-core. Of the natural fractures identified from the BHTV log, 343 were identified with high confidence, of which 4 had high acoustic amplitude signals, one had a mixed signal (high acoustic amplitude with, low amplitude borders), and the remainder (338) had low acoustic amplitude responses. Ten of the low amplitude fractures were further classified as fault planes, as they were observed to offset or truncate other features. The maximum fracture density observed from the BHTV log is 16 fractures per metre, and fracture widths fall within the range 0-20mm with approximately 35% greater than the modal fracture width (referred to as 'wide aperture fractures').

In contrast, the drill-core from this same imaged interval displayed 574 fractures. Of these, 376 were geological in origin (27 open, 349 filled with minerals), the remaining 198 features being drilling induced, as determined from observation from drill-core. Of these naturally occurring fractures, 325 had an observed acoustic response on the image. Where fractures were filled, measurements of fracture width were possible, and ranged between 2-6mm.

Table 2: Summary of the number of features identified from the BHTV log and the corresponding section of drill-core

Observations	Acoustic image	Drill-Core (of the depth interval imaged)
Natural Fractures	351	376
Drilling induced features, DITF's, or man-made core breaks	26 (DITF's)	191
Lithological & alteration features	4	12

4.2 Lithological and Alteration Features

In addition to fracture identification, the drill-core showed some alteration effects (Figure 3). Alteration patterns are occasionally seen in the acoustic image (Figure 3), where the boundary between altered and un-altered rock appears as a low amplitude, partial feature. This low amplitude, partial feature may reflect the concentration of iron oxides at the alteration boundary. No lithological structures were identified from the acoustic image, whereas a number of textural changes and stratification were noted from the drill-core, including changes in welding intensity, flow units, and interlayed lithologies.

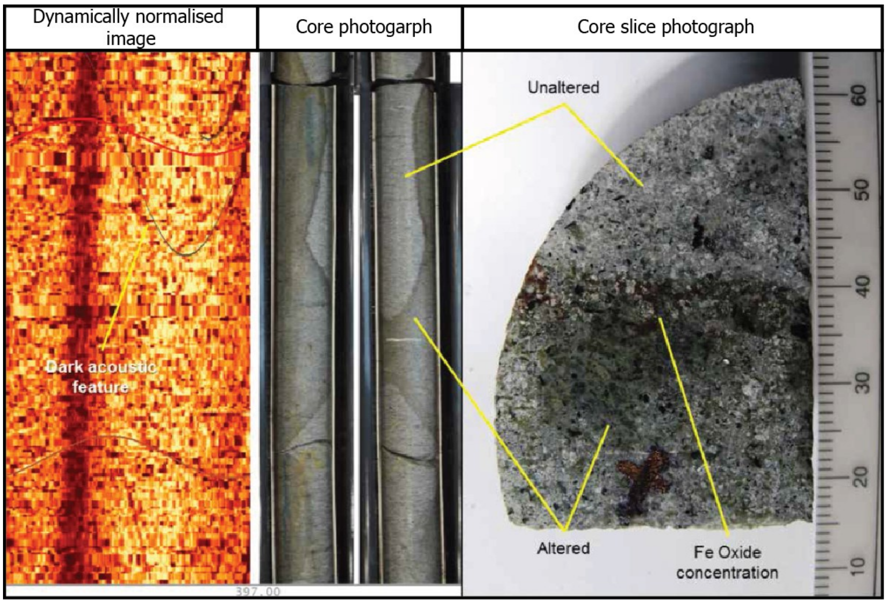

Figure 3: Alteration effects on the drill-core are imaged as low amplitude, partial sinusoids on the BHTV log.

4.3 Mineral Fill Identification

The comparison of the drill-core with the BHTV log has allowed for the acoustic response of various mineral fracture fills to be identified for the first time. This may allow identification of similar fracture fills on future BHTV logs run in similar geothermal environments. Of the fractures in the drill-core, 158 had a clay (smectite and kaolinite) fill, 40 had an iron oxide fill, 6 were filled with pyrite, 2 were filled with calcite, 1 was filled with indurated clay, and 142 had a mixed fill. The low amplitude acoustic responses (dark fractures) represented the iron oxide, pyrite, and clay fills, whereas the high amplitude acoustic responses (bright fractures) were either calcite or indurated clay (Figure 4). Indurated clay is has a high amplitude response due to the silica content which attenuates the sonic pulse from the tool. Fractures that had a mixed fill have a low amplitude response on the acoustic image due to the fact that clay is the most dominant component of the mixed fill.

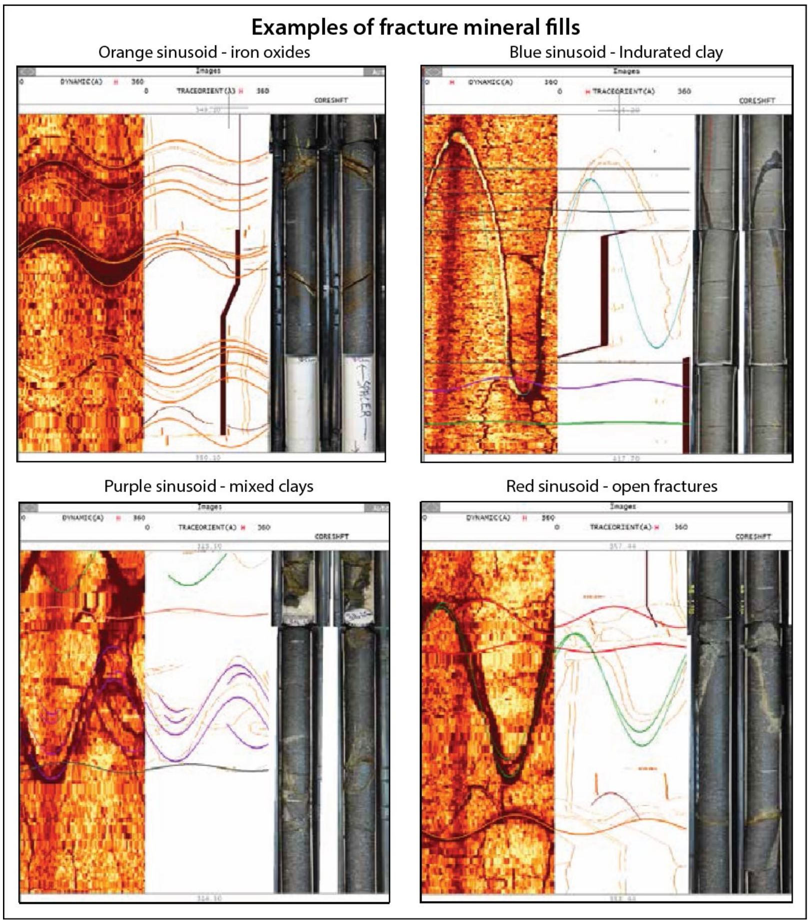

Figure 4: Example of some of the different mineral fracture fills seen in the drill-core, and their acoustic response in the BHTV log.

5 DISCUSSION

5.1 Correlation accuracy

The drill-core contained 51 fractures (~14%) which were not observed in the acoustic image. Their lack of appearance is mainly due to 'stick and pull' artefacts (Figure 2) degrading the image quality over the areas of the log where a corresponding feature would have been observed (~69%). Other features on the drill-core and not on the acoustic image are due to the features being beyond the resolution of the tool, or were not imaged as the fracture mineral fill lacked significant acoustic contrast to the borehole wall lithology (~31%).

In addition to the fractures not imaged in the BHTV log, there were just three features that were seen in the drill-core, but not in the acoustic image. Two of these were bands of alteration, similar to those in Figure 3, and one was a lithological layer feature.

In contrast, the BHTV log has 29 fractures that were not identified in the drill-core. A possible reason for this is due to 'crushed zones' of the drill-core. This is where drilling and movement of densely fractured or friable areas of drill-core have been damaged to the point where individual fracture identification is not possible. This is an example of where the BHTV log can give better information than the drill-core, as these 'crushed zones' of what is likely weak rock, are generally better preserved in the borehole wall (Figure 5).

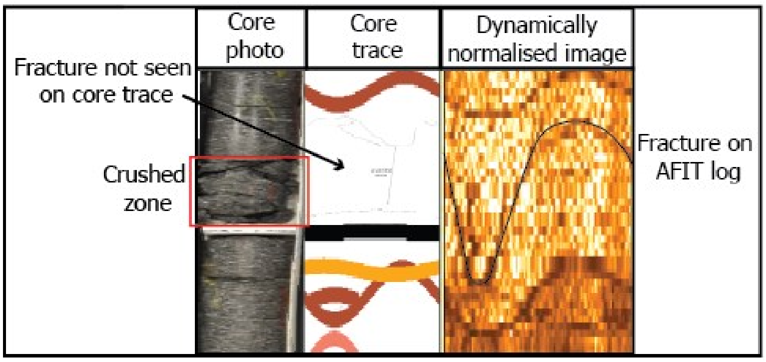

Figure 5: An example of the 'crushed zone' effect, where individual fractures are unable to be indentified from the drill-core/core trace, but are preserved in the borehole wall, and hence seen in the acoustic image.

The comparison has also allowed for open fractures in the drill-core to be further confirmed by identifying the corresponding dark sinusoids on the acoustic image. This indicates that the fracture in the drill-core is natural, as it propagates out into the formation, and is not just in the drill-core. This allowed for the re-classification of some of the low angle breaks, which were presumed to be drilling induced, as natural fractures, as these had a corresponding dark sinusoid in the acoustic image.

The drill-core allowed for a greater number of features to be identified, when compared to the BHTV log (Table 2). However, despite the fact that the BHTV log and the drill-core are not completely identical, they are very similar. For example when looking at fracture density, i.e. the number of fractures over a given depth, rather than individual fractures, the BHTV log and the drill-core match with only minor differences. This indicates that the AFIT LT tool is of a high enough resolution to capture the majority of important borehole information, to a level of accuracy that we believe is sufficient.

The accuracy of this BHTV log when compared to reality (i.e. the drill-core) reflects that the BHTV log was run in exceptionally good conditions due to slim-hole coring through stable rock providing a smooth borehole wall. In most drilling situations, this is unlikely to be the case due to bigger borehole sizes, variable drilling techniques and challenging lithologies, all of which increase the likelihood of the wellbore being irregularly shaped, over or under gauge, and/or unstable. All of these variables can affect BHTV log quality, and the attenuation of the acoustic signal, and is something that should be investigated as a continuation of this work.

5.2 Structural information

As the BHTV log provides the orientations of features, it was possible for the corresponding interval of drill-core to be orientated, and the true geological orientation of its fractures to be measured. As the BHTV log had imaged ~86% of the features present in the borehole, as determined from core correlation, the structural orientations made from drill-core were consistent with those made from the acoustic image. Additional data from features not observed on the BHTV log increased the number of fractures striking east-west. By orienting the drill-core, investigation into whether certain mineral fills favoured certain fracture orientations was possible. For example, smectite or mixed fill fractures showed a dominant north-south strike orientation, while open fractures were dominantly striking either north-south or east-west. Pyrite and iron oxide filled fractures were also dominantly north-south, but had a subordinate group of east-west also. The few calcite filled fractures displayed east-west strikes.

6 CONCLUSIONS

In this instance the AFIT LT tool performed well, and provided a high resolution image capable of representing the majority of the features seen on the drill-core. The acoustic image was particularly accurate with respect to capturing fractures of various types, but was also able to image certain alteration patterns, indicating that in a high quality image, that the AFIT LT tool has the potential to give textural information, as well as structural.

The discrepancy between features in the drill-core and features in the BHTV log was small. The drill-core revealed approximately 14% more geological features than the BHTV log. The discrepancies are attributed to 'stick and pull' artefacts, tool resolution, contrast between fracture fill and borehole lithology, with regard to those not observed on the acoustic image, and crushed zones affecting fracture identification from the drill-core.

Overall, the acoustic image was of high quality, and the correlation of the image with the drill-core has allowed for:

- Orientation of the drill-core;
- better natural fracture identification in the drill-core, where the same fracture is seen in the BHTV log, and;
- better understanding of the acoustic responses of different mineral fracture fills, which may aid future BHTV log interpretation in similar geothermal environments.

This study has demonstrated that BHTV logging in geothermal environments is a worthwhile activity, as the BHTV logs have high enough resolution, in order to collect, and allow a reasonably accurate interpretation of downhole geological information, where borehole conditions permit.

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