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Processing and analysis of high temperature geothermal acoustic borehole image logs in the Taupo Volcanic Zone, New Zealand

C. Massiot\textsuperscript{a,1,*}, D. D. McNamara\textsuperscript{b}, B. Lewis\textsuperscript{a}

\textsuperscript{a}GNS Science, Wairakei Research Centre, PB 2000, Taupo, New Zealand.
\textsuperscript{b}GNS Science, Avalon, PO Box 30-368, Lower Hutt 5040, New Zealand.

Abstract

Acoustic borehole televiewer (BHTV) logs provide direct observations of lithology, structure and \textit{in-situ} stress in reservoirs, essential for successful well targeting and field management. Analyses of BHTV logs acquired in twenty-three high temperature ($\leq 288^\circ$C) geothermal wells in the Taupo Volcanic Zone, New Zealand, resulted in the modification of BHTV processing techniques and the creation of a descriptive feature classification for hydrothermally altered, volcano-sedimentary-basement type reservoirs lacking other complementary information common in hydrocarbons or lower temperature geothermal systems. Lithological characteristics observed on these BHTV logs are presented, alongside an assessment of the reliability of the structural measurements and image interpretation.

Keywords: Acoustic borehole image log, high temperature geothermal, Taupo Volcanic Zone, feature classification, reservoir structure and stress, volcano-sedimentary lithologies
1. **Highlights**

- We analysed 23 acoustic borehole televiewer (BHTV) logs in the Taupo Volcanic Zone.
- We propose a new classification for lithological, structural and stress features.
- Patterns of volcano-sedimentary lithologies are presented.
- The accuracy and applicability of the BHTV interpretation results are discussed.
- The new techniques provide better input for geothermal reservoir characterisation.
2. Introduction

The use of geothermal resources is expanding worldwide, with new applications being investigated (Bertani, 2012; Saevarsdottir et al., 2014). Successful geothermal field development requires tapping reservoirs with high temperatures and high permeability but natural and enhanced geothermal systems (EGS) reservoirs often have low formation permeability. Thus the challenge is to successfully locate, target, and in some cases stimulate structures which act as fluid flow pathways. This benefits from an improved understanding of the nature of the lithologies, structural features, and in-situ stress field in a geothermal reservoir (Brace, 1980; Wood et al., 2001; Blackwell et al., 2007; Davatzes and Hickman, 2010; Dezayes et al., 2010; Cladouhos et al., 2011; Klee et al., 2011).

Continuous coring provides the best material to describe lithology and structure in a well (Genter and Traineau, 1996; Stimac, 2007) but is expensive and therefore uncommon. In the Taupo Volcanic Zone of New Zealand (TVZ), continuous coring is rare and confined to shallow, slim-hole monitoring (Rosenberg et al., 2009b) or exploration wells. Spot coring of a few meters is more common and provides valuable but limited structural information (Stimac et al., 2008; Boseley et al., 2012). Poor core recovery rates, especially in fractured formations, create data uncertainties. Drill cuttings are commonly sampled every five metres from the well during drilling but are small (typically <5mm), vulnerable to mixing within the well, and are susceptible to poor returns especially in permeable zones. All these factors limit geological interpretation from cuttings and preclude direct structural observation (Wood, 1996).

Acoustic borehole image logs compensate for or complement information obtained from cuttings and core by providing an oriented image of the inside of the borehole, with an image resolution of the order of ≤1 cm (Lagrabä et al., 2010). These logs provide information on lithological and structural features, horizontal in-situ stress orientations (Prensky, 1999; Poppelreiter et al., 2010) and also provide direct inputs for geomechanical models aimed at evaluating borehole stability and fracture slip tendency, as well as optimising well siting and
Acoustic imaging devices, also called borehole televiewers (BHTVs), use a rotating transducer to transmit and receive ultrasonic pulses around the borehole. Two types of information are recorded from the acoustic signal (Zemanek et al., 1970): (1) acoustic wave travel time, which provides information on borehole shape and (2) acoustic wave amplitude attenuation, which relates to the acoustic impedance of the borehole wall, depending on physical properties such as mineralogy, texture, fracturing and roughness, among others. Travel-time and amplitude signals are visualised as 360° images of the borehole wall, oriented using inbuilt triaxial accelerometers and magnetometers.

Compared to the hydrocarbons industry in which comprehensive wireline log suites are commonly acquired, the geothermal industry is data poor, with post-drilling wireline programmes often limited to pressure, temperature and fluid velocity (spinner) (PTS) logs which evaluate the productivity and injectivity of a well (Kamah et al., 2005; Grant and Bixley, 2011). This is due to the restricted number of logging tools, including imaging devices, able to operate at the high temperatures experienced in geothermal wells. Logging tools commonly deployed in hydrocarbon wells have limits of 177°C (Lagraba et al., 2010) and are not viable in hotter wells without initial quenching of the well to reduce temperature, which is not always possible or desirable. Standard BHTVs have been used in EGS, where the temperature did not exceed the tool specifications, to characterise natural fractures and in-situ stress (Tenzer et al., 1991; Dezayes et al., 1995; Genter et al., 1997; Valley and Evans, 2009), and to analyse the impact of stimulation on permeability (Evans et al., 2005).

Several high temperature logging tools were developed as part of the High Temperature Instruments (HiTI) project (Ásmundsson et al., 2014), including a high temperature BHTV tool (Acoustic Borehole Imager ABI85-92) developed by Advanced Logic Technology (ALT). This tool was the first to be deployed in wells with temperatures up to 300°C and can operate for up to thirty hours in 250-300°C environments. The tool is 85 mm diameter and operates in wireline mode with direct surface read-out using a high temperature logging cable. The
transducer operates at a frequency of 1.2 MHz and sonic pulses are reflected off a
rotating mirror enabling the tool to emit ultrasonic waves at 360°. The ABI85-92 is deployed in New Zealand by Tiger Energy Services (TES) under the trade
name ‘Acoustic Formation Imaging Technology’ (AFIT) tool. In TVZ geothermal wells, the tool is usually set to acquire 144 measurements per revolution
at a vertical logging speed of 2 - 3 m/min, equivalent to an image resolution of
about 5 mm vertically and 10 mm horizontally. To date, this design is the only
imaging device capable of operating in high temperature geothermal conditions.

Recently, BHTV logs have been acquired with this tool in a few high tem-
perature geothermal wells drilled into volcano-sedimentary formations (Davatzes
and Hickman, 2010, 2011; Batir et al., 2012; Blake and Davatzes, 2012). By con-
trast, numerous BHTV logs have been acquired in sedimentary formations by
the hydrocarbons industry, where their analysis and interpretation have been
standardised. Since 2009, twenty-three BHTV logs in seven high temperature
gelothermal fields have been acquired in the TVZ. These are the first BHTV im-
ages to directly observe the lithological and structural characteristics of the hy-
drothermally altered pyroclastic, volcanic and volcaniclastic formations, as well
as the greywacke basement, hosting New Zealand high temperature geother-
mal reservoirs. Historically these reservoirs have only been studied directly via
outcrops, drill cuttings and rare cores (Wood et al., 2001; Rosenberg et al.,
2009a,b; Milicich et al., 2013). The interpretation of TVZ BHTV logs has since
been used to refine lithological boundaries, better understand geothermal field
structure, and refine the locations of permeable zones (McLean and McNamara,
2011; Wallis et al., 2012; Massiot et al., 2013), which has provided insights into
the nature of reservoir fluid flow pathways.

The application of established BHTV log interpretation techniques to the
high temperature geothermal environment has necessitated adjustments to the
data processing and analysis methodology. This paper expands upon existing
acoustic borehole image processing and interpretation techniques applied to
geothermal settings, and highlights advances and observations made through
work carried out in the TVZ.
To maximise the accuracy and amount of data that can be extracted from BHTV logs, raw data needs to be processed and undergo rigorous quality control. The methodologies presented here are performed using the WellCAD and Recall® 5.4 software packages. Quality control and data processing includes, but is not limited to, assessment of tool acquisition parameters and orientation data, calculation of caliper logs, speed corrections to account for tool stick, and static and dynamic image normalisation (Rider, 1996; Hansen and Buczak, 2010). Much of this methodology is common to the hydrocarbon industry and low temperature geothermal data analysis, so the following sections will outline variations to data processing techniques that are unique to high temperature geothermal settings.

3.1. Caliper log calculations

Caliper logs measure the diameter of a borehole along its depth and can identify deviation from a cylindrical, smooth borehole wall (e.g. due to caving, spalling, ovalisation) which reduces image quality (Prensky, 1999). Caliper logs can aid in identifying borehole breakouts, which yield information about the local stress field (Zoback et al., 2003). Mechanical caliper tools have limited temperature ranges (< 177°C) and provide only 1 to 6 measurements for every depth a measurement is made. In contrast, caliper measurements can be calculated from the travel time signal of the BHTV logs for the full 360° circumference of the borehole, and in hotter wells. The caliper log is also integrated into acoustic image normalisation algorithms so it needs to be as accurate as possible.

Conversion from acoustic travel time to borehole diameter is performed using the velocity of sound through the borehole fluid, normally done for the default of pure water at atmospheric conditions (1487 m/sec). However, sound velocity is also affected by other borehole fluid characteristics, in particular the high ambient temperatures and pressures in geothermal wells (Davatzes and Hickman, 2010). This effect is mitigated by calibrating the caliper logs with the
speed of sound through water at the specific thermodynamic conditions (based on temperature while logging and external pressure measurements) experienced within the borehole (Wagner and Kretzschmar, 2007).

Caliper values from mechanical and BHTV logs are consistent in low temperature (< 177°C) wells where both logs are acquired. However, calculated caliper values are highly dependent on temperature and pressure in wells > 200°C as shown in Figure 1, which compares calibrated and non-calibrated, calculated caliper logs from a high temperature TVZ geothermal well. Caliper values calibrated for reservoir conditions are close to the expected 8.5 inch (216 mm) drilled diameter of the borehole, whereas non-calibrated caliper values are consistently higher. At higher temperature and pressure conditions the difference between calibrated and non-calibrated caliper values becomes more pronounced e.g. 0.56 inch (14 mm) difference at X300 m and 1.5 inch (38 mm) at X650 m.

The noise observed on the caliper log in Figure 1 results from small variations in borehole circularity in-between each travel-time measurement depth.

3.2. Image quality and artefacts

A comprehensive assessment of the image quality is important as it determines confidence in the identification of features and subsequent interpretation. Image quality is difficult to measure quantitatively as it depends on a combination of drilling, tool and geological factors. Qualitative assessment methods are commonly applied, after data processing and image normalisation (Davatzes and Hickman, 2009a; Valley and Evans, 2009; Garcia-Carballido et al., 2010). In this paper we adopt a five-part image quality classification. Quality is deemed good where >75% (270°) of the image is interpretable, moderate where 50-75% (180-270°) is interpretable, poor where 25-50% (90-180°) is interpretable, very poor where <25% (90°) is interpretable and bad when the image quality precludes any attempt of interpretation.

In BHTV logs acquired in the TVZ, poor image quality is often attributed to non-ideal borehole conditions (ovalisation, rugosity, spalling etc.), tool decentralisation, and the presence of image artefacts. Figure 1b shows a transverse
borehole cross-section extracted from the travel time signal in an inclined well in which a drillpipe keyseat has resulted in an irregular borehole wall shape. The result is a loss of acoustic signal over 25-50% of the circumference of the image (Figure 1c), and hence a moderate image quality classification.

Image artefacts are features that occur on BHTV logs but are not of geological origin (Lofts and Bourke, 1999; Barton and Moos, 2010), and therefore must be recognised to avoid confusion with natural features. Stick-and-pull and spiral hole artefacts are commonly observed on BHTV logs from the TVZ. To reduce signal attenuation in heavy drilling mud, a mud excluder apparatus can be fitted on the tool to reduce the distance travelled by the acoustic pulse through borehole fluid. The mud excluder has been used in TVZ geothermal wells drilled with water to acquire better quality images in boreholes where suspended particles or aeration were suspected to cause considerable signal attenuation. The mud excluder generates a new image artefact appearing as four, low acoustic amplitude, vertical bands, equally spaced around the borehole (Figure 2). These bands represent deflection of the acoustic pulse off the four non-magnetic struts that support the structure of the mud excluder.

4. Feature classification in geothermal settings

Natural and induced features are observed on BHTV logs. The detection of a feature depends on sufficient acoustic amplitude contrast with the host rock (Paillet, 1994). Acoustic amplitude is predominantly linked to mineralogy, but also to the grain size, compaction and roughness of the borehole wall. A lack of acoustic amplitude contrast is potentially significant where formations comprise a limited range of minerals, e.g. clay-filled fractures (low acoustic amplitude) may not be visualised on an image in a pervasively clay-altered formation (Valley, 2007; Davatzes and Hickman, 2010).

In hydrocarbon settings, classification of BHTV image features is commonly associated with a geological interpretation, made possible by abundant correlation with drill cores and other well logs. In sedimentary formations, planar
features may be differentiated as beddings rather than fractures, using only BHTV logs, by their lower dip angle (using e.g. 50° as the threshold) or the irregularity of dip angles associated with disturbed bedding. These classifications are usually made in combination with borehole image facies analysis (Samantray et al., 2010).

In geothermal wells, drill cores and BHTV logs are rarely obtained over the same intervals, either due to the lack of drill core, or in slim-hole coring operations due to the borehole diameter being too small for the high temperature BHTV. Even when different fracture types are identified on drill cores, it is not always possible to correlate them to specific feature characteristics on BHTV logs, as shown in sandstones and granite at the Soultz EGS (Genter et al., 1997). A purely descriptive classification of features observed on the BHTV logs is thus encouraged to allow multiple subsequent interpretations as recommended by Trice (1999). Distinctions between structural (fractures, faults, stress fabrics) and lithological (foliation, bedding or flow banding) features are made in BHTV log interpretations where possible (Batir et al., 2012; Blake and Davatzes, 2012). Fault zones textures and mineralised dykes in dioritic formations were identified on the basis of their geometry, acoustic amplitude and electrical resistivity on both BHTV and electrical image logs at the Coso Geothermal Field (Davatzes and Hickman, 2009a). Davatzes and Hickman (2009b) dissociate beddings and foliations from fractures on BHTV logs by their close spacing, sub-parallelism, and uniform acoustic impedance in volcanic and sedimentary formations at the Desert Peak EGS. In the absence of other well logs, or to complement them, additional criteria are used to allow further feature interpretation. Valley (2007) and Genter et al. (1997) classify the fractures as ‘open’ when the feature is observed on both the amplitude and the travel-time image upon the assumption that they extend beyond the borehole wall, even if they are not necessarily fluid flow pathways. These authors also measure the continuity of the fractures around the borehole image and use it as an indicator of the likelihood that the fracture propagates into the formation. The ratio of partial to fully continuous structures has been used to estimate fracture length (Ozkaya, 2003). A quality
ranking is also typically applied as part of established classification schemes, e.g. Blake and Davatzes (2012) for in-situ stress features. Data from lower quality features are generally not used for interpretation, increasing dataset reliability. Building on the existing work and concepts, a classification scheme for use in TVZ geothermal settings for both natural and induced features has been developed and is discussed below (Table 1).

4.1. Natural features

Natural features include those that are lithological or structural in nature (Table 1). A ‘layer’ is a lithological feature appearing as alternating bands of variable acoustic amplitude (Figure 2), or as abrupt, large scale variations that may represent a change of formation. ‘Fractures’ are structural features discordant from the overall acoustic amplitude of the host rock. If the structural feature offsets another natural feature, it is classified as a ‘fault’ (Figure 3a). Occasionally the offset is too large to be measured and instead the feature appears truncated. A fault may also be inferred by juxtaposition of two lithologies that display different acoustic amplitude levels separated by a ‘fracture’.

Further description of structural and lithological features is made based on their planarity, continuity and angular relationship to other features in close proximity. Figure 3 displays examples of the various categories of structural features and angular relationships. A feature is classified as planar if it displays a perfect sinusoidal form. Non-planar fractures may be the product of multiple shearing events (Davatzes and Hickman, 2010). Feature continuity is also evaluated: a continuous feature can be fully (360°) traced across the image, whereas a discontinuous feature can only be traced intermittently over >75% of the image, and a partial feature is visible over only 25 to 75%.

The angular relationship of a given feature to other nearby features that are within 1 m above or below is described. Features that cross-cut each other are labelled ‘cross-cutting’ and a group of features with similar orientation (≤15° dip and azimuth difference) that do not cross-cut each other are defined as ‘parallel’. ‘Solitary’ features have neither parallel nor cross-cutting relationships.
The apparent fracture aperture is defined as the width of the discordance scaled to the borehole diameter. Increases in apparent aperture commonly occur where features (natural or induced) intersect and result in spalling from the borehole wall (Figure 3a). Therefore, the estimated aperture of a structure is measured at the sinusoid inflexion point which is less subject to spalling, or, at a representative location on the sinusoid away from feature intersections. The apparent aperture of a structure intersecting the borehole at an angle is greater than the actual aperture (measured perpendicular to the structure surface) and is corrected following Barton and Zoback (1992).

Two levels of confidence are assigned to all natural features. High confidence features are those picked continuously with the least ambiguity. Low confidence features are more difficult to accurately select on an image and tend to form only partial or discontinuous sinusoids. Low confidence features are used with caution and only to reinforce interpretations made from high confidence features, or, in imaged intervals with an absence of high confidence features.

4.2. Induced features

Induced features form on the borehole wall during drilling as a result of the local stress field around the borehole. In vertical wells (assuming one of the principal stresses is vertical) the orientation of borehole breakouts, drilling induced tensile fractures (DITF) and petal centreline fractures (PCF) (Table 1, Figure 4) indicate the orientations of the minimum ($S_{h_{\text{min}}}$) and maximum ($S_{H_{\text{max}}}$) horizontal stress directions (Zoback et al., 2003). Other induced features known as thermally induced borehole elongations form sub-parallel to $S_{H_{\text{max}}}$ at the borehole wall (Bérard and Cornet, 2003), but have not been observed to date in the TVZ. The lengths of DITFs and borehole breakouts are measured to calculate weighted averages of the stress orientations. The width of borehole breakouts and the angle of DITFs to the borehole axis are integrated in the stress magnitude calculations. PCFs are induced mode I fractures that nucleate in the formation, open in the $S_{h_{\text{min}}}$ direction and propagate inward (toward the borehole) ahead of the drill or core bit (Li and Schmitt, 1998). PCFs appear
on BHTV logs with a curved portion (petal fracture) that becomes a pair of
vertical fractures parallel to the borehole axis (centreline fractures, Figure 4). In
contrast to DITFs which they resemble, the centreline portions of PCF features
are oriented < 170° from each other around the borehole. The average orienta-
tion of the two centrelines of a single PCF feature provides an approximate
orientation of $S_{hmin}$ (Davatzes and Hickman, 2010).

In the TVZ, wells deviated 0–17° are empirically defined as vertical (Massi-
siot et al., 2013), and the vertical stress ($S_v$) is the maximum principal stress
($\sigma_1$) (Hurst et al., 2002; Townend et al., 2012). $S_{hmin}$ and $S_{Hmax}$ orientations
derived from induced features in TVZ vertical wells (McLean and McNamara,
2011; Wallis et al., 2012; Massiot et al., 2013) are in agreement with surface ob-
servations and focal mechanisms. Petal centreline fractures (PCFs) significantly
increase the size of the $S_{hmin}$ orientation dataset in TVZ wells, enhancing con-
fidence in its measurement. $S_{hmin}$ orientations derived from PCFs are similar
to values from borehole breakouts and are perpendicular to sub-perpendicular
to the $S_{Hmax}$ orientations derived from DITFs.

5. Data processing and interpretation

The feature processing and interpretation carried out to date in geother-
mal BHTV studies in New Zealand combines and expands previous work and
standard practices carried out on hydrocarbons and other geothermal datasets.
Results from BHTV log analyses provide vital insight into the macroscopic
structures in a well but cannot be used directly. A correction method for a
systematic orientation bias is presented here, followed by some characteristics
of lithological and alteration features observed in the TVZ BHTV logs.

5.1. Method for natural feature orientation bias correction

Planar features appear as sinusoids across the BHTV log. The sinusoids are
manually selected using Recall™ 5.4, where their orientations are calculated
automatically taking into account caliper measurements and orientation of the
well. The fracture orientation distribution is used to evaluate controls on fluid
flow in the reservoir and assist in targeting future wells. However, a bias in
structural orientation data is introduced by the under sampling of features ori-
ented sub-parallel to the borehole axis (Barton and Zoback, 1992; Peter-Borie
and Gentier, 2011). To mitigate the sampling bias, a statistical correction is
applied following Terzagui (1965). A statistical weight $w$ is applied to each fea-
ture depending on the acute angle ($\delta$) between the plane normal to a fracture
and the well trajectory (Equation 1):

$$w = \frac{1}{\cos(\delta)}$$ (1)

To prevent a single feature with a $\delta$ approaching $90^\circ$ from dominating any
given fracture population, we use an estimation of the $w$ factor error ($w_\epsilon$) (Equa-
tion 2) (Yow, 1987):

$$w_\epsilon = \frac{\cos(\delta)}{\sin(90 - \delta - \epsilon)} - 1$$ (2)

where $\epsilon$ is the error associated with the orientation measurement (angular
resolution), with a maximum allowable value for $w_\epsilon$ of 20% (Priest, 1993). This
 corresponds to a maximum allowed value of $w = 10$ for BHTV logs acquired in
the TVZ ($\epsilon \approx 2.5^\circ$).

The $w$ parameter is calculated for each feature using the well trajectory at
the associated depth. Each feature and its descriptors are then replicated $w$
times, an operation which creates a new corrected data set with an increased
proportion of fractures oriented sub-parallel to the borehole axis. Massiot et al.
(2012) details the modification of various fracture sets in TVZ BHTV logs in
relation to regional structural considerations. This correction is particularly
important in the tectonic settings of the TVZ where most fractures have high
dip angles ($> 60^\circ$) and wells are rarely deviated $> 30^\circ$ from vertical (i.e. rarely
plunging $< 60^\circ$).
5.2. Characteristics of TVZ lithologies and hydrothermal alteration patterns

In the TVZ, layering has been observed on outcrops and drill cores as bedding in lacustrine and fluvial deposits, successions of airfall deposits in ignimbrites, ash layers and flow banding within lava flows (Steiner, 1977) and the inherited bedding of the metamorphosed sandstones and shales comprising the greywacke basement (Beetham and Watters, 1985). Primary permeability can occur along these features as well as lithologically controlled structures (e.g. brecciated carapaces or margins of lava flows, rubbly tops of successive lava flows) and dykes boundaries (Rissmann et al., 2011; Milloy and Lim, 2012). In addition, non-welded ignimbrites and unconsolidated, pumiceous and tuffaceous breccias may host intrinsic permeability (Rosenberg et al., 2009a; Bignall et al., 2010). Results of BHTV log interpretations in the TVZ provide some of the first in-situ observations of these boundaries and textures. Advances presented here include a description of layering observed in volcaniclastic deposits, a differentiation of lithologies, and constraints on the occurrence of magnetite (primary or hydrothermal) from correlation of magnetic field fluctuations and drill cuttings descriptions.

Variations between and within lithologies can be observed on BHTV logs from changes in acoustic amplitude. Inter-formational boundaries have been observed on TVZ acoustic images between ignimbrites and lava flows, and between successive lava flows. Figure 5 shows a marked change in the acoustic character of the image coinciding with a boundary between two rhyolites defined from cuttings descriptions. Alternating bands of variable acoustic amplitude related to the superposition of beds of variable composition and/or texture within fluvial and lacustrine deposits have been observed (Figure 2). Zones of variable welding in an ignimbrite observed in cuttings, show that acoustic amplitude increases with the degree of welding (Figure 6). Indeed, harder, welded formations are more likely to form smooth borehole walls, generating high acoustic amplitudes (Zemanek et al., 1970).

The magnetic field, recorded as part of the BHTV data set, allows the delineation of intervals containing magnetite (Figure 7). High frequency fluctuations
(±1 μT) of the magnetic field correlate to the presence of pervasive magnetite alteration noted in drill cuttings. In addition, the presence of magnetite-bearing dykes known from drill cuttings correlates to 2–3 μT magnetic field fluctuations. Care should be taken when considering mineralogy as a source of magnetic field variation when there is a lack of direct evidence of magnetic minerals (i.e. drill core/cuttings) as drilling-related phenomena may also perturb the magnetic field (e.g. shavings from a drill bit being lodged in the borehole wall). Image orientation is less reliable where magnetite (primary or hydrothermal) exists, although the examination of the BHTV tool orientation sensors response suggests that the perturbation is small, and no significant change in feature orientation is observed in the magnetite-bearing intervals described herein.

6. Discussion

6.1. Caliper calculations

In addition to the temperature and pressure conditions of the borehole fluid, the composition of the fluid plays a role in attenuation and speed of the acoustic pulse. The caliper calculations from the BHTV travel time data discussed here are performed assuming pure water but ideally should account for variations in composition, density, salinity, steam and particulate matter present in the borehole fluids during image acquisition. In practice, these effects are mitigated by additional, appropriate calibrations when applicable (mud density, salinity), by cleaning the well before logging (decreasing the amount of particulate matter in the borehole fluid), and by applying a constant pumping rate while logging (homogenising the borehole fluid pressure along the well).

6.2. Data processing and interpretation

Useful information on layering, texture and alteration of the host rock has been retrieved from the correlation of TVZ BHTV logs and drill cuttings. However there still remains the task of accurate classification of layering in TVZ type lithologies (i.e. whether layers represent ash layers, variable welding in
ignimbrites, etc.). Layers have not commonly been observed in BHTV logs in the TVZ, and their interpretation is equivocal particularly where there is no useful corroborating information to be obtained from cuttings or drill core, or where neither of these exist (total circulation losses while drilling).

Further calibration between core and image logs will improve the identification of lithological features to complement the rare and sporadically distributed core correlation studies performed to date. The addition of other logging tools may also aid interpretation of layer features. High (300°C) temperature spectral gamma ray logs, such as acquired with the SGR85 developed by ALT, would aid the interpretation of alteration zones and help identify changes in primary mineralogy allowing more detailed lithological logging from BHTV logs. Resistivity image logs are more sensitive to changes in lithology than acoustic images, with lithological fabrics having been successfully identified in lower temperature geothermal wells (Davatzes and Hickman, 2010). There are however still significant technological hurdles to increasing the temperature rating of a resistivity imaging device and the resolution of an acoustic imaging device.

Measurement of apparent fracture aperture suffers from an under-sampling of (1) narrow fractures which are below the detection limit or resolution of the BHTV, and (2) wide aperture fractures which have a lower probability to be encountered and may be a composite of a number of narrow fractures. These biases are known as truncation and censoring, respectively, and can be mitigated through statistical analysis (Laslett, 1982; Barton and Zoback, 1992; Pickering et al., 1995). Drill core analyses from TVZ geothermal wells indicate fractures have apertures commonly ≤10 mm. Fractures ≤5 mm wide are not resolved by the BHTV, except in the rare case of a very high acoustic amplitude contrast between the feature and the host rock. The majority of apertures measured on BHTV logs vary between 15 and 30 mm. These are likely overestimated due to scattering of the ultrasonic pulse at the edge of the fracture where the roughness of the borehole wall is high (Davatzes and Hickman, 2010). Wider apertures (up to metre scale) correspond to densely fractured zones where individual features are beyond the resolution of the image, and are often associated with spalling.
from the borehole wall. As a result, the apparent aperture is treated as a maximum estimate of the fracture aperture.

The delineation of fracture sets is improved by the correction of the orientation bias, but other information such as fracture spacing and length are not taken into account and require further statistical analysis. Fracture density is also heavily influenced by image quality, and comparisons of fracture densities are therefore only made between intervals of similar image quality ranking.

Other factors can alter the fracture density measurements. Based on systematic comparison between a BHTV log and drill cores, Genter et al. (1997) found a 50% under-sampling of fractures identified on the BHTV log in unaltered massive granite, but 85% under-sampling in altered and fractured zones. Similarly, comparison between drill core and BHTV logs from the TVZ also indicates various degrees of under-sampling of fractures on the BHTV log. The study of a high image quality BHTV log over a weakly altered and poorly fractured ignimbrite provided a 90% correlation to fractures observed on the cores. On the other hand BHTV logs from other lithologies (intensely altered porphyritic andesite; intensely veined and weakly altered greywacke; and moderately altered, strongly welded lithic-rich ignimbrite) displayed poor to no core correlation. This is due to a combination of: (1) poor image quality, (2) lack of significant acoustic amplitude contrast between fractures and host rock on the BHTV log, and (3) feature aperture being smaller than the image resolution.

While the use of PCFs is valuable in increasing confidence in the $S_{\text{hmin}}$ orientation, there is still room for further development in analysing the stress field in the TVZ. In deviated wells, it is unlikely that any of the principal stresses are parallel to the borehole axis, precluding the assumption that in-situ stress features directly indicate the orientation of the horizontal stress directions. Methods based on the width of borehole breakouts or the angle of inclined DITFs exist to model stress in inclined boreholes (Zoback, 2010; Thorsen, 2011) but few of these features have been observed in the TVZ BHTV logs. In addition, stress determination methods in inclined wells rely on the availability of minimum stress magnitudes estimated from extended leak-off or mini-frac well
tests (White et al., 2002) which are scarce in the TVZ. They also rely on accurate measurements of the strength of the reservoir rock, which are difficult to constrain for high-temperature reservoir conditions. Finally, the thermal stress due to the temperature difference between the formation and the borehole fluid is, although poorly constrained, likely to be significant in high temperature geothermal wells.

6.3. Permeability

An inherent limitation of all BHTV log interpretation is the inability to assess structural connectivity away from the borehole surface and the structure’s contribution to well permeability. The combination of a descriptive classification scheme with limited feature types and additional descriptors allows further interpretation of the nature of a structure, i.e. whether it is closed or open. To aid with assessment of a structure’s permeability, BHTV logs are combined with hydrothermal alteration observations and other wireline log data (Sausse et al., 2006), although the latter are rarely available in high temperature wells. In the TVZ, variations in temperature and fluid velocity have been correlated to individual fractures identified on TVZ BHTV logs and refined depths and intervals of well permeability (McLean and McNamara, 2011; Wallis et al., 2012). Some permeable zones identified on PTS logs have been correlated to clusters of cross-cutting fractures, but not to clusters of parallel fractures (Wallis et al., 2012). The presence of magnetite-bearing dykes located using the magnetic field log from the BHTV has also been correlated to permeability (Massiot et al., 2013). Structural permeability can also be assessed by identifying critically stressed fractures that are more likely to be open for fluid flow (Barton et al., 1997), though this approach is limited in the TVZ in the absence of reliable stress magnitude measurements and rock strength data at reservoir conditions. Ongoing measurements and well testing performed by the New Zealand geothermal research and industry community will help resolve these issues in the future.
7. Conclusion

BHTV logs have been acquired for the first time in the hydrothermally altered volcano-sedimentary and greywacke lithologies hosting TVZ geothermal reservoirs (New Zealand). This paper summarises advances made in the formative years of BHTV log acquisition and interpretation in high temperature, TVZ geothermal wells. Methodologies, classification schemes and interpretive techniques have been constructed to account for extreme conditions of data acquisition, the nature of the geology of various geothermal reservoirs, geothermal drilling practices, and other geothermal logging data (e.g. PTS logs). It is envisioned that in coming years more advances will be made as more image logs, drill core and reservoir information are gathered, new well testing and rock deformation experiments are performed, and other, complementary high temperature logging tools (e.g. full wave-form acoustic, resistivity imager) are developed.

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<table>
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<th>Feature class</th>
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|              |                          | High confidence | Low confidence                                                                 | - Depth  
| Lithological (Natural) | Layer                  | Pair of planar features, defining zones or bands of different acoustic amplitude that can be observed >270° around the borehole | Nature (lithological boundary or intraformational fabric)  
|              |                          |                           | Orientation (dip magnitude, dip direction)  
|              |                          |                           | Thickness  
|              |                          |                           | Relationship to other features |
|              |                          |                           | Partial (observed over 90° to 270° around the borehole) or poorly resolved layer |
| Structural (Natural) | Fracture                | Planar, discordant feature that can be observed >270° around the borehole | - Depth  
|              |                          |                           | Acoustic amplitude (high or low)  
|              |                          |                           | Orientation (dip magnitude, dip direction)  
|              |                          |                           | Apparent aperture  
|              |                          |                           | Relationship to other features  
|              |                          |                           | Planarity  
|              |                          |                           | Fault offset |
|              |                          |                           | Partial (observed over 90° to 270° around the borehole) or poorly resolved, apparently discordant feature |
|              |                          |                           | Not applicable |
|              |                          |                           | Planar, high or low acoustic amplitude, discordant feature (fracture) that is observed >270° around the borehole and displaces or truncates other features |
|              |                          |                           | Not applicable |
|              |                          |                           | Planar, discordant feature that appears to be part of a pair but the second feature, oriented 170-180° apart, is masked by poor image quality |
|              |                          |                           | Not applicable |
|              |                          |                           | Paired, low acoustic amplitude, vertical to sub-vertical, straight, "J" or "S" shaped features, 170-180° apart |
|              |                          |                           | Single, low acoustic amplitude, vertical to sub-vertical feature that appears to be part of a pair but the second feature, oriented 170-180° apart, is masked by poor image quality |
|              |                          |                           | Not applicable |
|              |                          |                           | Paired, wide, low acoustic amplitude, approximately vertical, irregularly shaped feature, 170-180° apart |
|              |                          |                           | Not applicable |
|              |                          |                           | One petal (P) and two centreline (CL) fractures. CL: paired, thin, low acoustic amplitude, vertical to sub-vertical features <170° apart. P: partial fracture that occurs at the end of two centrelines |
|              |                          |                           | Not applicable |
|              |                          |                           | Depth  
| Drilling Induced Tensile Fracture (DITF) |                       |                           | Orientation (azimuth)  
|              |                          |                           | Shape  
|              |                          |                           | Length  
|              |                          |                           | Angle to the borehole axis |
|              |                          |                           | Depth  
|              |                          |                           | Orientation (azimuth)  
|              |                          |                           | Width  
|              |                          |                           | Length |
|              |                          |                           | Depth  
|              |                          |                           | Orientation (average of the two centreline azimuths)  
|              |                          |                           | Relationship to other features |
|              |                          |                           | Not applicable |
|              |                          |                           | Not applicable |

Table 1: Feature classification used for analysis of BHTV logs in TVZ geothermal wells
Figure 1: a) Effect of integrating temperature and pressure logs in caliper calculations from BHTV logs. b) Borehole cross-section showing irregular borehole shape (NW-N-NNE, blue brackets) over the grey shaded area on a). c) BHTV travel time and amplitude image showing poor image quality (blue brackets) due to irregular borehole shape. All BHTV images in this paper are displayed unwrapped, with 0° azimuth (N) to the left, 180° azimuth (S) at the centre, and 360° azimuth (N) to the right. Depths are shown as e.g. ‘X300’ where ‘X’ is a numerical value omitted for data confidentiality purposes. Data courtesy of Rotokawa Joint Venture Ltd.
Figure 2: Succession of low and high acoustic amplitude layers in a bedded sequence of fluvial and lacustrine sediments (labelled L1 to L6) and low confidence layers (labelled LCL) in the Waipara Formation, Wairakei Geothermal Field. ME indicate the four vertical bands of low acoustic amplitude generated by the mud excluder. a) Statically normalised BHTV image. b) Interpretive diagram. Data courtesy of Contact Energy Ltd.
Figure 3: BHTV logs showing examples of fracture morphology and angular relationship (defined in Table 1). a) Images showing low acoustic amplitude fractures of high and low confidence, a fault showing truncation of other features, and spalling observed between two closely spaced fractures. Accompanying caliper log correlates with the structural features. (b) Images showing high acoustic amplitude fractures of high and low confidence. (c) Images showing a non-planar low amplitude fracture. Data courtesy of Contact Energy Ltd.
Figure 4: a) BHTV image log from a vertical well with natural and induced features. b) Interpretive schematic diagram identifying DITFs (purple lines), a PCF composed of two centrelines (CL) (orange lines) and a petal fracture (P) (green line), and a natural fracture (NF) (blue line). c) Theoretical diagram showing the locations of induced features on a cross-section of a borehole. Data courtesy Contact Energy Ltd.

Figure 5: BHTV logs showing a non-planar lithological boundary (blue dashed line) between the fractured base of a coherent rhyolite overlying a flow-banded, microspherulitic rhyolite. Data courtesy of Contact Energy Ltd.
Figure 6: Correlation between acoustic amplitude and variation of welding in an ignimbrite. Changes of logging run are indicated as they cause localised variations in acoustic amplitude. Depths are shown as e.g. 'XX00' where 'XX' is a numerical value omitted for data confidentiality purposes. Data courtesy Contact Energy Ltd.
Figure 7: a) Magnetic field signal from a lithology containing no magnetite. b) Magnetic field signal from a lithology containing disseminated hydrothermal magnetite alteration (2–5 vol. % of the rock). c) Magnetic field signal over an interval containing a magnetite-bearing dyke intruding a non-magnetite bearing lithology. *Data courtesy of Mighty River Power Ltd.*


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