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

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ABSTRACT

Acoustic borehole televiewer (BHTV) logs provide direct observations of lithology, structure and *in situ* stress in reservoirs, essential for successful well targeting and field management. Analyses of BHTV logs acquired in twenty-three high temperature (≤288 °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.

1. 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 <5 mm), 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 (Lagraba 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 production (Zoback and Healy, 1992; Zoback, 2010; Barton and Moos, 2010). 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

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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 30 h 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 temperature geothermal wells drilled into volcano-sedimentary formations (Davatzes and Hickman, 2010, 2011; Batir et al., 2012; Blake and Davatzes, 2012). By contrast, 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 geothermal fields have been acquired in the TVZ. These are the first BHTV images to directly observe the lithological and structural characteristics of the hydrothermally altered pyroclastic, volcanic and volcaniclastic formations, as well as the greywacke basement, hosting New Zealand high temperature geothermal 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.

2. Quality control and processing for geothermal BHTV logs

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.

2.1. 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 1–6 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/s). 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 Fig. 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 in. (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 in. (14 mm) difference at X300 m and 1.5 in. (38 mm) at X650 m. The noise observed on the caliper log in Fig. 1 results from small variations in borehole circularity in-between each travel-time measurement depth.

2.2. 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, 2009; Valley and Evans, 2009; Garcia-Carballido