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GEOTHERMAL STRUCTURAL GEOLOGY IN NEW ZEALAND: INNOVATIVE CHARACTERISATION AND MICRO-ANALYTICAL TECHNIQUES

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ABSTRACT

Many of New Zealand's geothermal reservoirs are hosted in rocks with low intrinsic permeability. As such, successful development of these resources relies on understanding the role subsurface structures, such as fractures and faults, play in reservoir permeability. Further complexity is added to this understanding due to the constantly evolving permeable nature of these geothermal reservoir structures. The same fractures and faults which operate as interconnected, open, fluid flow pathways, can also behave as fluid flow barriers due to geothermal mineral precipitation over time.

Increased industry application of borehole logging technology, and the development of innovative geothermal data processing and interpretation, has allowed structural geologists to make advances in characterising the subsurface structure of the Taupo Volcanic Zone. These novel data reveal structural heterogeneity at a variety of scales, from changing dominant orientations across the Taupo Volcanic Zone, to decimetre changes in fracture orientation within a single well. Additionally, these techniques allow observation of the variability in *in situ* horizontal stress directions for the first time, revealing active subsurface structures.

At a much smaller scale, the application of novel, advanced, microscopy techniques to analyse the micro-structure of geothermal vein minerals provides information on evolving geothermal reservoir fluid properties, and stress conditions. Crystallographic analysis of microstructures found in geothermal calcite veins can provide insight into the differential stress history of the reservoir, while the operation of temperature dependent, calcite crystal slip systems, may provide a tool to record evolving geothermal reservoir temperatures.

1. INTRODUCTION

An increase the utilisation of natural and enhanced geothermal resources has required geoscientists to explore the nature of permeability in reservoirs hosted within crystalline, volcanic and plutonic rock, and indurated, metamorphic basement [Wood et al., 2001; Sausse et al., 2006; Blackwell et al., 2007]. Successful development of these reservoirs is dependent on understanding permeability, which can be dominantly controlled by faults and fractures, [Brace, 1980; Dezayes et al., 2010]. As such, structural information, including spatial distribution, orientation, aperture, and fracture fill, is vital to the development of any geothermal reservoir hosted in igneous or metamorphic rocks.

In New Zealand, the geothermal resources of the Taupo Volcanic Zone (TVZ) are frequently hosted in lithologies with low primary permeability such as andesite and rhyolite lavas (~$9.95\text{x}10^{-9}$ – $1.68\text{x}10^{-7}$ md), welded and indurated ignimbrites and tuffs, pervasively silicified volcaniclastics and, greywacke basement rock (~4.89x10-7 md) [Bignall et al., 2010; Siratovich et al., 2014; 2016; McNamara et al., 2014]. As such data on the reservoir structure and stress is required to understand how geothermal fluids move within them. Acquisition of this data has traditionally been limited in the TVZ due to limited surface exposure, few drill-cores, difficulty with geophysical imaging (e.g. seismic reflection) of the sub-surface, and operational challenges and technological constraints on traditional logging technology (Hunt et al., 2009; Massiot et al., 2015).

Advances in technology and innovative application of technology, particularly borehole imaging equipment (Ásmundsson et al., 2014; Massiot et al., 2015; McNamara et al., 2015) and scanning electron microscopy (McNamara et al., 2016), have facilitated the acquisition of much needed, novel datasets on the subsurface structure of New Zealand's geothermal systems. In this paper I layout the highlights of these innovative structural geology studies and comment on the potential future development of this branch of structural geoscience in New Zealand geothermal resources.

2. BOREHOLE IMAGE LOGGING

Borehole image logs acquire oriented images of the inside of the borehole, with a resolution of the order of ~ 0.5 to 1 cm depending on the type of image log acquired. Lithological and structural data within a well can be obtained using these borehole imaging tools, as well as data on *in situ* horizontal stress field orientations. The data generated from borehole imagery provides direct inputs for reservoir geomechanical models that assist with determining the best orientation for borehole stability while drilling, and the tendency of fractures and faults to slip or dilate assisting with optimising well siting and production (Zoback, 2010).

Borehole image logging can be done using either acoustics or resistivity, each of which measure different physical properties which are complimentary to each other (Prensky, 1999). Acoustic imaging devices, also called borehole televiewers (BHTVs), use a rotating transducer to transmit and receive ultrasonic pulses around the borehole. BHTV tools capture two types of information; 1) acoustic wave travel time, which can provide information on borehole shape, and 2) acoustic wave amplitude attenuation, which is related to the acoustic impedance of the rock the borehole has been drilled into. The latter is effected mainly by the physical properties of the rocks such as mineralogy, texture, fracturing, roughness etc. and so geological features are identified when a contrast in acoustic impedance exists between lithological beds, across a fractures, etc. BHTV logs take travel-time and amplitude data and visualises them as unrolled 360° images of the borehole wall interior, which are oriented using inbuilt triaxial accelerometers and magnetometers.

Resistivity image logging presses pads fitted with arrays of electrodes maintained by a constant electrical potential against the borehole wall. The current emanating from each electrode is measured as the pads move along the borehole wall. Measurements from all the electrodes are combined to generate electrical conductivity images of the borehole interior. Geological features are imaged through observation of variance in electrical conductivity between, for example, fractures and host rock.

Both borehole logging techniques have their own pros and cons in what, and how much geological information they capture (Prensky, 1999; Davatzes and Hickman, 2010). BHTVs commonly provide better visualisations of structural and *in situ* stress features than electrical image logs. On the other hand, resistivity logs provide higher resolution and reveal more information on lithology, texture, and finer scale layering and fracturing.

2.1 Geothermal Borehole Image Logging

In comparison to the hydrocarbon industry, where comprehensive suites of wireline logs are acquired as standard datasets, the geothermal industry is data poor. Often logging in geothermal wells is limited to fluid velocity (spinner), pressure and temperature (PTS) logs used to evaluate well performance (Grant and Bixley, 2011). An important driver behind the sparse acquisition of logging data geothermal wells is the restricted number of logging tools, including imaging devices, able to operate at the high temperatures experienced in geothermal wells. Conventional logging tools have limits of ~177°C and are not viable in hotter wells without initial quenching of the well to reduce temperature, which is not always possible or a desirable process to carry out in a borehole.

Some enhanced geothermal system (EGS) projects have utilised standard image logging tools in their wells, though in these cases the well temperature did not exceed the tool limits (Tenzer et al., 1991; Barton et al., 1998; Valley and Evans, 2009). Several other geothermal borehole image studies have utilised enhanced borehole imaging tools for higher temperature wells e.g. the Schlumberger hot-hole Formation Microscanner (FMS) at the Coso Geothermal Field (Davatzes and Hickman, 2010). In more recent years, a number of logging tools were developed as part of the High Temperature Instruments (HiTI) project, including a high temperature BHTV tool (Acoustic Borehole Imager ABI85-92) developed by Advanced Logic Technology (ALT) (Ásmundsson et al., 2014). The ABI85-92 can operate up to fifteen hours at 275°C and for shorter durations at 300°C (Halladay et al., 2010).

This tool was first deployed in Iceland in early 2010, in wells with temperatures reaching up to 300°C (Massiot et al., 2010; Batir et al., 2012). Since then it has been adopted for use in a number of geothermal wells in the U.S.A. (Davatzes and Hickman, 2009; 2010), in systems dominated by volcano-sedimentary formations. To date, this BHTV tool design is the only device capable of operating in high temperature geothermal conditions. Equivalent high temperature capability has not yet been developed for electrical (resistivity) imaging devices.

2.2 Geothermal Borehole Image Logging in New Zealand

Since 2009 the ABI85-92 BHTV tool has also been deployed in New Zealand by Tiger Energy Services (TES) under the trade name 'Acoustic Formation Imaging Technology' (AFIT) tool. In TVZ geothermal wells, logs are commonly set to acquire 144 measurements per revolution at a vertical logging speed of 2–3 m/min, equivalent to a resolution of about 5 mm vertically and 10 mm horizontally.

Approximately thirty image logs (mostly BHTV logs) have been acquired in six high temperature, geothermal fields in the TVZ (Figure 1). These images have provided the first direct observation of the *in situ* lithological, structural, and stress characteristics of the volcano-sedimentary deposits and greywacke basement formations which host New Zealand's geothermal resources. Given the unique geological setting these image logs were obtained within, and that they were the first datasets of their kind for the TVZ, their processing, analysis and interpretation would need to be specifically designed to reflect this. Massiot et al. (2015) undertook a study that utilising image log processing and interpretation techniques previously optimised for sedimentary environments and modified them to meet the unique characteristics of TVZ geothermal systems. Such developments included caliper log calibrations to account for the variable speed of sound (important for BHTV logging) in fluids at high temperatures, identification of new image artefacts resulting from the geothermal BHTV tool design, and an image feature classification scheme specifically designed for the hydrothermally altered, volcano-sedimentary-basement type reservoirs typical of the TVZ.

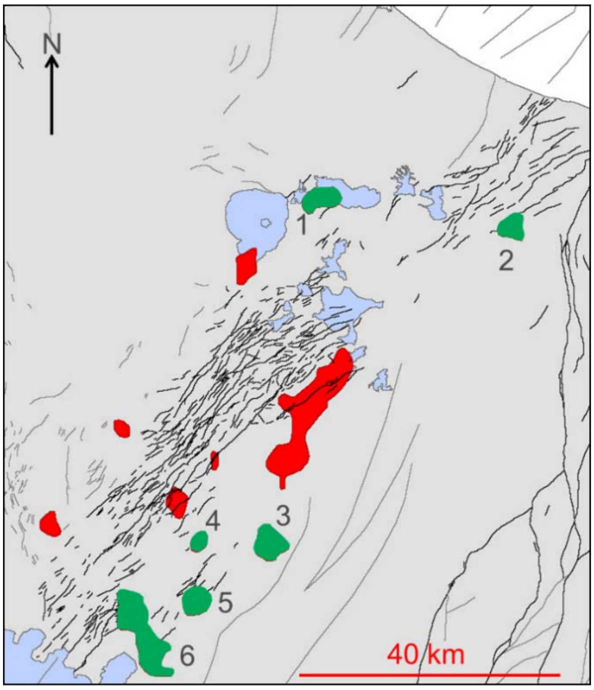

Figure 1: Map of the Taupo Volcanic Zone showing geothermal fields (green = borehole images acquired, red = borehole images not acquired to date), active faults (dark grey lines). 1 = Taheke, 2 = Kawerau, 3 = Ohaaki, 4 = Ngatamariki, 5 = Rotokawa, 6 = Wairakei-Tauhara.

The data acquired from image logs in New Zealand geothermal fields has since been used to determine the fracture scale structural character of geothermal reservoir rocks (McNamara et al., 2016; McNamara et al., 2015), determine the statistical distributions of fracture parameters in andesite lava reservoirs (Massiot et al., 2015), link lithological variation to fracture character (Massiot et al., 2013; Wallis et al., 2012), refine the location of permeable zones (McNamara et al., 2015; Mclean and McNamara, 2011), analyse the *in situ* stress field orientations (McNamara

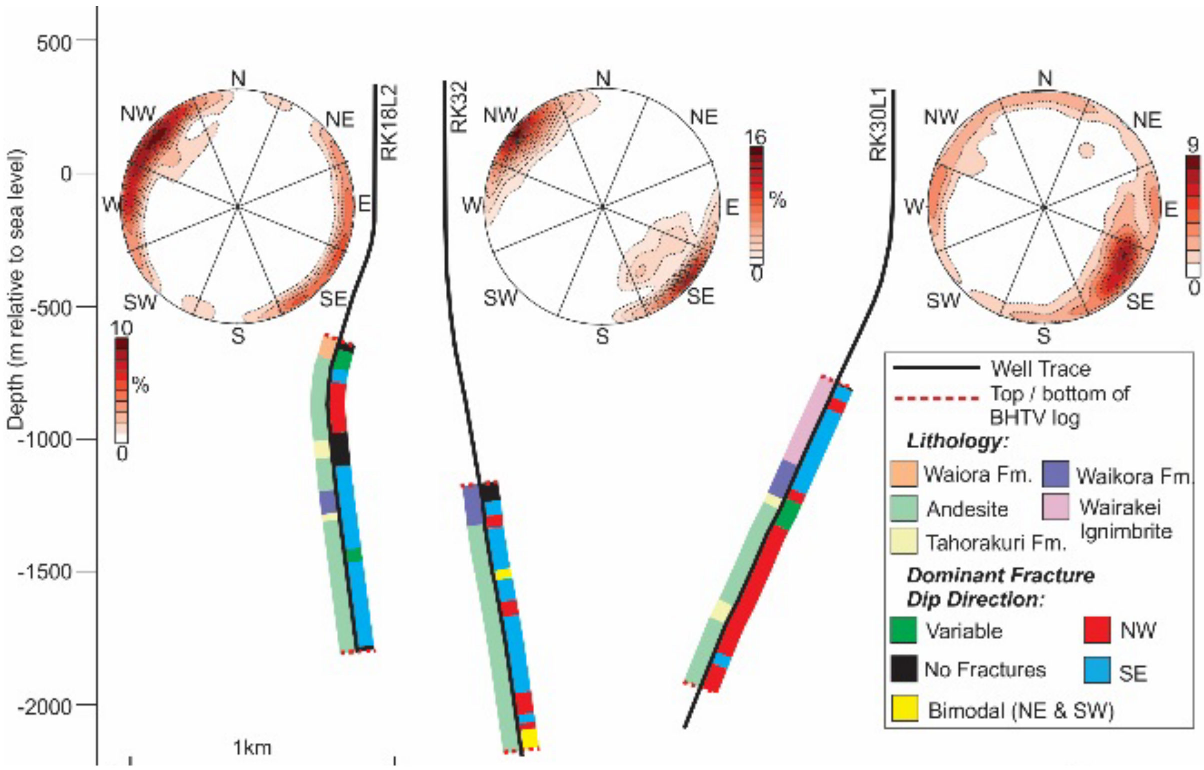

Figure 2: From McNamara et al., 2015. Wells RK18L2, RK30L1 and RK32 with left side of well traces coloured for lithology (determined from drill-cuttings/core and geological modelling), and the right side coloured for dominant fracture dip direction as determined from BHTV image logs. Contoured, lower hemisphere stereonets of poles to planes show fracture orientation pattern for each well.

et al., 2015; Massiot et al., 2013), and determine the location and orientation of recently active reservoir structures (McNamara et al., 2015; Davidson, 2014). This paper will highlight some key findings that have resulted from the study of this novel dataset to New Zealand geothermal.

2.2.1 Subsurface Structural Characterisation

The three borehole images acquired in the Rotokawa Geothermal Field are the most intensely studied of any New Zealand geothermal field (McNamara et al., 2015; Massiot et al., 2015), despite other fields with a higher number of wells images (e.g. Wairakei; McNamara et al., 2016).

While the overall fracture orientations determined from BHTV logs in the Rotokawa Geothermal Field displayed a pattern typical of the TVZ (NE-SW striking, dipping >70°) and agreed with the character of modelled and mapped structures in the Rotokawa Geothermal Field, variability at various scales was still evident (Figure 2). Field-scale variability exists in the form of changing dominant fracture dip directions. Fractures in the most north-eastern well (RK30L1) display a dominant NW dip direction while the most south-western well (RK18L2) has a dominant SE dip direction pattern. This variation is thought to relate to well proximity to field scale, subsurface faults which have antithetic dips to each other, matching the dominant fracture dips observed from BHTV logs. Similar variation in fracture orientation can be observed across the Wairakei-Tauhara Geothermal Field as well (McNamara et al., 2016).

Well scale variation in fracture orientation is also apparent. The dominant fracture strike orientation (NE-SW) is observed in all three wells, yet N-S fracture strike orientations are also common, and rare E-W and NW-SE strike orientations can be observed. Vector azimuth plots of BHTV log fracture dip directions for each well reveal depth intervals in individual wells where the dominant fracture dip direction is antithetic to the overall well fracture dominant dip direction. This is best observed in well RK32 where intervals of dominantly SE and NW dipping fractures alternate. This alternating pattern of fracture dip direction implies that while a well may display a dominant fracture orientation related to its proximity to a nearby large scale fault, localised intervals of antithetic fractures may be representative of smaller antithetic faults to that fault.

2.2.2 Lithological Control on Structural Orientation

In the Wairakei Geothermal Field, current data from BHTV logging, indicates some depth related structural orientation variation may be related to lithology (Figure 3). BHTV logged intervals of Tahorakuri and Waiora formations in a number of wells across the field show NW dipping fracture dominate, while in logged intervals of the Waikora Formation SE fracture dip orientations are more prevalent. Some subordinate structural orientations observed from the BHTV data in the Wairakei Geothermal Field show concentrations within specific lithologies e.g. the Mapara 2 Rhyolite contains numerous E-W striking fractures, and the Wairakei Ignimbrite has a high proportion of N-S striking fractures.

In the Kawerau Geothermal Field, BHTV data from two geothermal wells was compared with detailed lithological study of the greywacke basement drill cuttings (Wallis et al., 2012). It is suggested from correlations made from these datasets that lithology controls fracture behaviour, such that larger aperture fractures and more intersecting fractures are observed over depth intervals dominated by greywacke sandstone compared to those intervals with higher proportions of argillite.

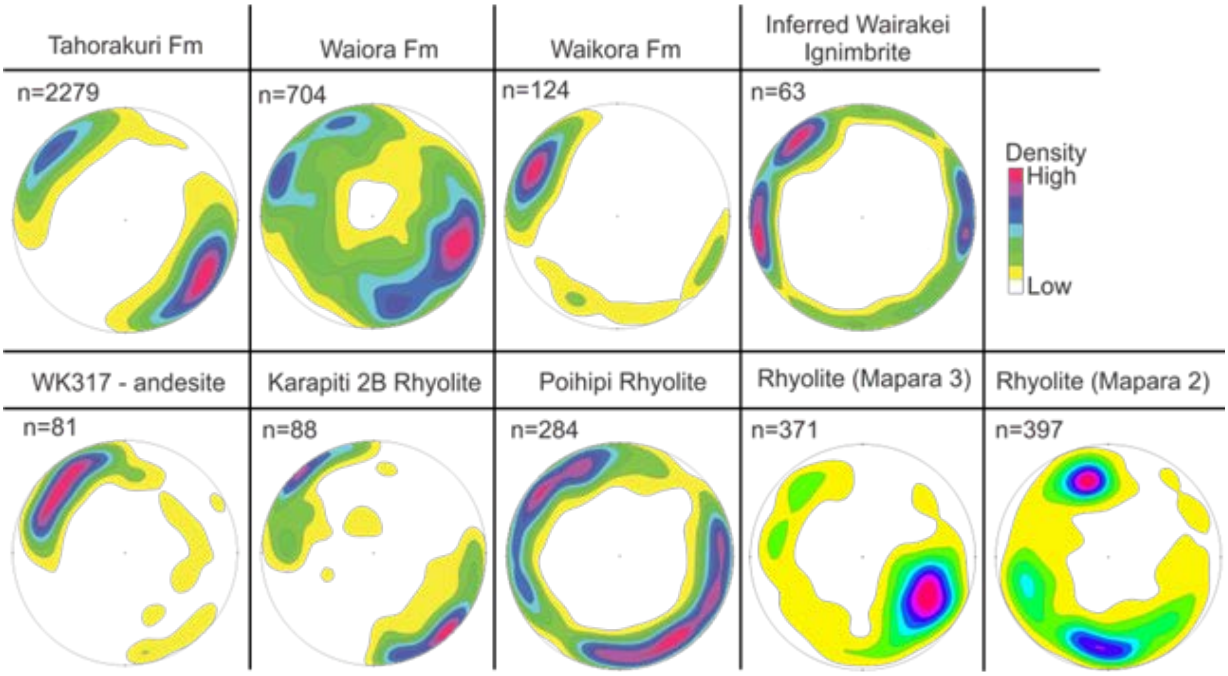

Figure 3: From McNamara et al., 2016. Fisher contoured, lower hemisphere stereonets of poles to planes of structures identified within the various lithologies over which a BHTV log was acquired in the Wairakei Geothermal Field.

It will be important to determine the geological cause of lithological controls on fracture development, as this will have significant impact on field development and production from structurally controlled permeability. Variable structural orientation patterns in different rock types may be related to rock properties such as layering, strength, brecciation layers, alteration intensity, or it may be due to external factors such as stress field variations, fluctuation thermal effects on rock mechanics.

2.2.3 Identifying Permeable Structures and Refining Fluid Flow Intervals

Permeable zones are commonly identified in New Zealand geothermal wells using pressure, temperature, spinner/fluid velocity (PTS) logging. Variation and relationships in PTS logging data down a well allow depth intervals where hot or cold fluid if entering or exiting the well. By combining this data with the structural observations made from image logging, the properties of fracture controlled fluid flow pathways can be determined and assessed, and feed zone intervals can be refined, providing better accuracy of fluid movement which allows for a better understanding of the geothermal plumbing systems.

In the Rotokawa geothermal field permeable zones were projected onto structural data from wells which had been image logged. This correlation indicated that all but one permeable zone contains wide aperture fractures, and approximately two thirds contain high fracture densities. Fracture orientations in fluid flow zones had dominant SE dip directions with subordinate populations dipping NW, W, and E (McNamara et al., 2015). Similar relationships between fluid flow zones and wide aperture fractures are noted in the Kawerau and Wairakei Geothermal Fields as well (Wallis et al., 2012; McLean and McNamara, 2011).

Common to all observations of structural patterns in fluid flow zones from BHTV logs in New Zealand geothermal wells is that a significant number of fractures with similar properties are also observed along the well outside of the permeable zones. These fractures are thought to have some fundamental difference that results in them not being part of a connected fluid flow network. It may be that these fractures are sealed by hydrothermal alteration, have poor connectivity away from the borehole (fracture length remains unknown), or may have an orientation contrary to that required for slip in the given stress state of the reservoir.

2.2.4 Characterising Stress Field Orientations and Identifying Active Structures

Induced features can form on the borehole wall during drilling in response to the local stress field. In a vertical well, assuming one of the principal stresses is vertical, the orientation of induced features such as borehole breakouts, drilling induced tensile fractures, and petal centreline fractrues can be used to infer the orientations of the minimum (S_{hmin}) and the maximum (S_{Hmax}) horizontal stress directions (Zoback et al., 2003).

In the Rotokawa Geothermal Field, observed *in situ* horizontal stress field orientations (NE-SW S_{Hmax} and NW-SE S_{hmin}) from three BHTV logs were consistent with the extensional setting of the TVZ, stress orientations (McNamara et al., 2015). However, it was found that the horizontal stress field orientations were variable across the field, and with depth in individual wells. A difference of ~19° - 24° in the mean S_{Hmax} direction is observed between well RK18L2, and wells RK30L1 and RK32. In wells RK30L1 and RK32 S_{Hmax} orientations show stress field rotations over numerous <10m depth intervals. Well RK18L2 contains a bi-modal S_{Hmax} direction pattern related to depth, produced by a horizontal stress field rotation of ~32°.

These perturbations in the *in situ* horizontal stress field orientation at Rotokawa are inferred to be generated by recent slip on a fault or fracture plane (McNamara et al., 2015). For example, recent activity on the Production Field Fault may have perturbed the *in situ* stress field enough to explain the difference between S_{Hmax} orientations observed in well RK18L2 and those in wells RK32 and RK30L1. The more localised stress field rotations were observed to occur over discrete fractures on the BHTV logs, implying those fractures have also been recently slipping. When analysed, the dominant orientation of potentially active structures is NE-SW striking, dipping both NW and SE, which is consistent with the regional strike of active faults in the TVZ.

3. SCANNING ELECTRON MICROSCOPY AND FRACTURE SEALING

Fracture sealing via mineralisation is known to create barriers to fluid flow in geothermal reservoirs, decreasing permeability and reducing the reservoir's effectiveness (Batzle and Simmons, 1976; Genter et al., 2010). Therefore, study of fracture sealing processes is vital to discerning the evolution and sustainability of fractured geothermal systems. One investigative approach to understanding the mechanisms of fracture sealing is to map the microstructural and chemical patterns of fracture sealing minerals. Analysis of these types of data is made difficult due to the fracture sealing processes being highly sensitive to a wide range of factors; degree of fluid supersaturation, anisotropic growth kinetics (mineral growth), rates of local deformation, and rates of fluid transport (Hilgers et al., 2004). While vein mineralogy has been studied in a number of places, until recently, these advanced microscopy techniques had not been applied to a geothermal setting such as the TVZ (McNamara et al., 2016).

A combined use of cathodoluminesence (CL), energy dispersive X-Ray Spectroscopy (EDX), and electron backscatter diffraction (EBSD; Prior et al., 2009) have all been combined in a study of calcite sealed fractures from the Kawerau Geothermal Field (McNamara et al., 2016). CL and EDX were used to acquire images of the nature and composition of chemical zonation in the vein calcite crystals, and EBSD was carried out to rapidly acquire the crystallographic orientation datasets of the calcite vein crystals (Figure 4).

Observations of calcite crystal morphology, chemical zonation, and crystallographic orientation from two sealed geothermal fractures in the greywacke basement of Kawerau Geothermal Field reveal multiple fracture sealing mechanisms in operation; asymmetrical syntaxial growth, and growth in free 3-D space. Additionally, this combined EBSD/EDX/CL study of calcite sealed fractures in revealed promise in this technique as a tool in understanding reservoir evolution. For example, observed lattice distortions associated with the elongated growth of bladed calcite crystals points toward a defect-originated growth mechanism for bladed calcite. If so, this micro-texture may provide a way of indicating low levels of supersaturation within the geothermal fluid the calcite crystals precipitated from.

EBSD mapping of calcite veins in the Kawerau Geothermal Field revealed a range of misorientation axes and a systematic difference in misorientation axes between different vein generations. This implies that the slip systems by which calcite is deforming in each vein varies, which is important as the operation of different slip systems in calcite can be temperature dependent under particular strain rates. Future study of this phenomenon in a series of cross-cutting calcite veins could therefore potentially provide information on the deformation and thermal history of the greywacke basement reservoir rock at Kawerau.

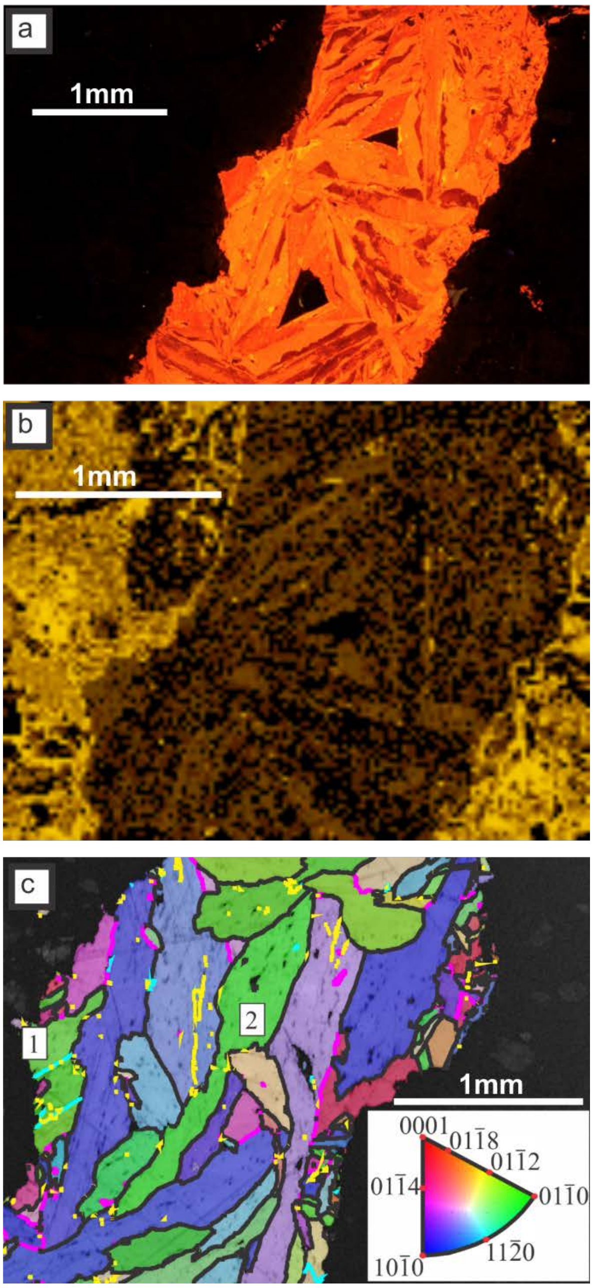

Figure 4: Images of a bladed calcite vein from greywacke basement reservoir of Kawerau Geothermal Field a) CL image, b) Fe EDX count map, c) Band Contrast map with an Inverse Pole Figure colour scale in the sample's Z direction and Grain Boundary overlay (black = 10° grain boundary, light-blue = 5° sub-grain boundary, yellow = 2° sub-grain boundary, pink = calcite e-twin).

Calcite twinning, or a lack thereof, can provide useful information on the evolution of this greywacke basement geothermal reservoir. In the studies Kawerau calcite veins, a distinct lack of twinning and micro-deformation (sign of deformation) was observed in bladed calcite crystals. A lack of calcite twinning can be used to imply the fracture containing these crystals represents the most recent brittle deformation event experienced by the greywacke basement in this area of the Kawerau Geothermal Field. The low occurrence of twinning in these calcite crystals also implies that since this fracture was sealed there has been little strain accumulation in the rock, or if there has none of it is accommodated by the calcite in this fracture. In other veins where calcite twinning was observed have the potential to record the differential stress magnitudes that this reservoir rock has been subjected to over time, though more study into these calcite veins is required to obtain accurate data.

4. SUMMARY

The advent of borehole image logging in New Zealand geothermal fields has facilitated the acquisition of the first, direct structural measurements from the subsurface. This data has provided information on the structural architecture of a number of geothermal reservoirs, the orientations of fluid flowing fractures, and those that have recently been tectonically active, and finally has provided information on the *in situ* stress field orientations and variability thereof.

Future work with borehole imaging methods and datasets will further deepen our understanding of subsurface structure and stress in the TVZ, and they role they play in geothermal expression. Fracture datasets from borehole imaging can be applied to the determination of the distribution of various fracture attributes (width, spacing, orientation) in order to build fracture models of TVZ geothermal reservoirs (Massiot et al., 2015). These fracture models may be then utilised in flow models to truly understand the structural contribution to geothermal fluid flow, and how it responds to various production and injection scenarios.

The pilot study into the microstructure and chemistry of calcite veins in the Kawerau Geothermal Field has highlighted this techniques potential as a tool to provide us with information on geothermal fluid, reservoir deformation, and temperature evolution. Further studies on calcite will enhance the potential applicability of this technique to help us understand unique geothermal problems such as reservoir scaling. Additionally, similar investigations into other common fracture sealing minerals such as quartz, epidote, zeolite, and clay may reveal yet further combined microstructural-microchemical tools for reservoir characterisation.

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REFERENCES

Ásmundsson, R., Pezard, P., Sanjuan, B., Hennings, J., Deltombe, J-L., Halladay, N., Lebert, F., Gadalia, A., Millot, R., Gibert, B., Violay, M., Reinscg, T., Maisse, J-M., Massiot, C., Azaïs, P., Mainprice, D., Karytsas, C., Johnston, C.: High temperature instruments and methods developed for supercritical geothermal reservoir characterisation and exploitation – The HiTI project, *Geothermics*, 40, 90-98, (2014).

Barton, C.A., Hickman, S.H., Morin, R., Zoback, Z.D., Benoit, D.: Reservoir-scale fracture permeability in the Dixie Valley, Nevada, Geothermal Field, *Proceedings of SPE/ISRM Rock Mechanics in Petroleum Engineering Conference*, (1998).

Batir, J., Davatzes, N.C., Ásmundsson, R.: Preliminary model of fracture and stress state in the Hellisheidi Geothermal Field, Hengill Volcanic System, Iceland, in *Proceedings of the Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford*, (2012).

Batzle, M.L., Simmons, G.: Microfractures in rocks from two geothermal areas, *Earth and Planetary Science Letters*, 30, 71-93, (1976).

Bignall, G., Rae A., Rosenberg, M.D.: Rationale for targeting fault versus formation-hosted permeability in high-temperature geothermal systems of the Taupo Volcanic Zone, New Zealand, *Proceedings, World Geothermal Congress*, (2010).

Blackwell, D. D., Negraru P. T., Richards, M.C.: Assessment of the enhanced geothermal system resource base of the United States, *Natural Resources Research*, 15, 283–308, (2007).

Brace, W. F.: Permeability of crystalline and argillaceous rocks, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 17, 241–251, (1980).

Davatzes, N.C., Hickman, S.: Stress, fracture, and fluid-flow analysis using acoustic and electrical image logs in hot fractured granites of the Coso Geothermal Field, California, U.S.A., in Poppelreiter, M., Garcia-Carballido, C., and Kraaijveld, M. eds., Dipmeter and borehole image log technology: *AAPG Memoir* 92, p. 259–293, (2010).

Davatzes, N.C., Hickman, S.: Fracture, stress and fluid flow prior to stimulation of well 27-15, Desert Peak, Nevada, EGS project: *Proceedings of the 34th workshop on geothermal engineering, Stanford*, (2009).

Davidson, J.: Permeability of Geothermal Systems, from Reservoir to Surface, PhD Thesis, University of Canterbury, New Zealand, (2014).

Dezayes, C., Genter A., Valley, B.T.: Structure of the low permeable naturally fractured geothermal reservoir at Soultz, *Comptes Rendus Geoscience*, (2010).

Grant, M.A., and Bixley, P.F., 2011, Geothermal Reservoir Engineering: Academic Press, Burlington, USA.

Genter, A., Evans, K., Cuenot, N., Fritsch, D., Sanjuan B.: Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS), *Competes Rendus Geoscience*, 342, 502-516, (2010).

Halladay, N., Deltombe, J., Naisse, J., Johnston, C., Lebert, F.: Borehole Instruments for Supercritical Geothermal Reservoirs: *Proceedings World Geothermal Congress*, Bali, Indonesia, 25-29 April, (2010).

Hilgers, C., Dilg-Gruschinski, K., Urai, J.L.: Microstructural evolution of syntaxial veins formed by advective flow, *Geology*, 32, 261-264, (2004).

Hunt, T.M., Bromley, C.J., Risk, G.F., Sherburn, S., Soengkono, S.: Geophysical investigations of the Wairakei Field. *Geothermics*, 38, 85–97, (2009).

Massiot, C., McNamara, D.D., Lewis, B.: Processing and analysis of high temperature geothermal acoustic borehole image logs, New Zealand, *Geothermics*, 53, 190-201, (2015).

Massiot, C., McNamara, D.D., Nicol, A., Townend, J.: Fracture width and spacing distributions from borehole televiewer logs and cores in the Rotokawa Geothermal Field, New Zealand, *World Geothermal Congress*, (2015).

Massiot, C., McNamara, D.D., Lewis, B.: Interpretive review of the acoustic borehole image logs acquired to date in the Wairakei-Tauhara Geothermal Field*: GNS Science Report 2013/04*. 32 p, (2013).

Massiot, C., Asmundsson, R., Pezard, P.A.: Achievements and Ongoing Progress of the European HiTI Project: High Temperature Instruments for Supercritical Geothermal Reservoir Characterization and Exploitation: *Proceedings World Geothermal Congress*, (2010).

Mclean, K., McNamara, D.D.: Fractures interpreted from acoustic formation imaging technology: correlation to permeability: *Proceedings of the Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford*, (2011).

McNamara, D.D., Lister, A., Prior, D.J.: Calcite sealing in a fractured geothermal reservoir: Insights from combined EBSD and chemistry mapping, *Journal of Volcanology and Geothermal Research*, 323, 38-52, (2016).

McNamara, D.D., Bannister, S., Villamor, P., Sepúlveda, F., Milicich, S.D., Alcaraz, S., Massiot, C.: Exploring structure and stress from depth to surface in the Wairakei Geothermal Field, New Zealand, *Proceedings 41st Workshop on Geothermal Reservoir Engineering*, (2016).

McNamara, D.D., Massiot, C., Lewis, B., Wallis, I.C.: Heterogeneity of structure and stress in the Rotokawa Geothermal Field, New Zealand, *Journal of Geophysical Research: Solid* Earth, 120, (2015).

McNamara, D.D., Faulkner D., McCarney, E.: Rock properties of greywacke basement hosting geothermal reservoirs, New Zealand: preliminary results, *Proceedings, Thirty-Ninth Workshop on Geothermal Reservoir Engineering*, (2014).

Prensky, S.E.: Advances in borehole imaging technology and applications, in Lovell, M., Wiliamson, G., and Harvey, P.K. eds., Borehole Imaging: Application and Case Histories. Special Publication No. 159*, The Geological Society Publishing House, London*, 1-43, (1999).

Sausse, J., Fourar, M., Genter, A.: Permeability and alteration within the Soultz granite inferred from geophysical and flow log analysis, *Geothermics*, 35, 544–560, (2006).

Siratovich, P.A., Heap, M.J., Villeneuve, M.C., Cole, J.W., Kennedy, B.M., Davidson, J., Reuschlé, T.: Mechanical behaviour of the Rotokawa andesites (New Zealand): Insight into permeability evolution and stress-induced behaviour in an actively utilised geothermal reservoir, *Geothermics*, 64, 163-179, (2016).

Siratovich, P. A., Heap, M. J., Villenueve, M. C., Cole, J.W., Reuschlé, T.: Physical property relationships of the Rotokawa Andesite, a significant geothermal reservoir rock in the Taupo Volcanic Zone, New Zealand, *Geothermal Energy*, 2, 1-31, (2014).

Tenzer, H., Mastin, L., Heinemann, B.: Determination of planar discontinuities and borehole geometry in the crystalline rock of borehole GPK-1 at Soultz-Sous-Forets, *Geothermal Science and Technology*, v. 3, no. 1-4, p. 31–67, (1991).

Valley, B., Evans, K.F.: Stress orientation to 5 km depth in the basement below Basel (Switzerland) form borehole failure analysis, *Swiss Journal of Geosciences*, v. 102, no. 3, p. 467–480, (2009).

Wallis, I.C., McNamara, D.D., Rowland, J.V., Massiot, C.: The nature of fracture permeability in the basement greywacke at Kawerau geothermal Field, New Zealand: *Proceedings of the 37th Workshop on geothermal Reservoir Engineering, Stanford*, (2012).

Wood, C. P., Brathwaite R. L., Rosenberg M. D.: Basement structure, lithology and permeability at Kawerau and Ohaaki geothermal fields, New Zealand, *Geothermics*, 30, 461-481, (2001).

Zoback, M. D. (2010), Reservoir Geomechanics, Cambridge University Press, Cambridge, U.K.

Zoback, M.D., Barton, C.A., Brudy, M., Castillo, D.A., Finkbeiner, T., Grollimund, B.R., Moos, D.B., Peska, P., Ward, C.D., Wiprut, D.J.: Determination of stress orientation and magnitude in deep wells: *International Journal of Rock Mechanics and Mining Sciences*, v. 40, no. 7-8, p. 1049–1076, (2003).