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ScienceDirect

Energy Procedia 125 (2017) 273–282

Energy Procedia

www.elsevier.com/locate/procedia

European Geosciences Union General Assembly 2017, EGU
Division Energy, Resources & Environment, ERE

Characterizing the subsurface structure and stress of New Zealand's geothermal fields using borehole images

David D. McNamara[a]*, Cécile Massiot[b], Sarah M. Milicich[b]

[a]*National University of Ireland Galway, University Road, Galway, Ireland*
[b]*GNS Science, 1 Fairway Drive, Lower Hutt, New Zealand*

Abstract

Borehole imaging captures geological information on lithology, structure, and stress in the Earth's subsurface. This paper synthesises currently analysed borehole imaging data acquired in geothermal fields in the Taupo Volcanic Zone. Structure and stress orientations agree with the tectonic trend, though display variation between and within geothermal fields. Structural variability is related to larger scale rift fault architecture, while stress orientation variations are related to active structures. Borehole images also provide information on structural fluid flow pathways in TVZ geothermal fields showing structures with NE-SW and E-W strike orientations and wide fractures occur within fluid flow zones.

Peer-review under responsibility of the scientific committee of the European Geosciences Union (EGU) General Assembly 2017 – Division Energy, Resources and the Environment (ERE).

Keywords: geothermal; New Zealand; Taupo Volcanic Zone; fluid flow; fractures; stress

1. Introduction

The Taupo Volcanic Zone (TVZ) contains much of New Zealand's high enthalpy geothermal resources, most of which are hosted within volcanic deposits and crystalline plutonic rocks, or indurated, metamorphic, greywacke basement. The permeability within these geothermal reservoirs is invariably dominated by faults and fractures, with only small contributions made by intrinsic, porosity type permeability [1,2,3]. As such, geological investigation that

* Corresponding author. Tel.: +353-9-149-3069.
E-mail address: david.d.mcnamara@nuigalway.ie

1876-6102
Peer-review under responsibility of the scientific committee of the European Geosciences Union (EGU) General Assembly 2017 – Division Energy, Resources and the Environment (ERE).
10.1016/j.egypro.2017.08.176

reveals insights into the architecture of New Zealand's geothermal structural (fault and fracture) system, and the in-situ stress regime acting upon it, is vital for a resource's development.

In the TVZ more common techniques for characterizing the subsurface structure are not available. Seismic surveys reveal little about subsurface structures due to interference from high natural ground level noise and high attenuation [4]. Other geophysical methods commonly utilized for investigating subsurface architecture are limited to inferring the presence of larger scale crustal structures at depth [5,6,7]. Surface exposure of deeper lithostratigraphic units is limited, and active fault mapping and outcrop fracture measurements only reveal the structural characteristics of the uppermost lithostratigraphic layers of the TVZ volcaniclastic fill [8,9]. Three-dimensional structural modelling of TVZ geothermal fields and the basement structures of the entire TVZ are limited by the well density of individual fields and scale restrictions of geophysical data input [10].

Historically, borehole imaging technology had not been applied in wells drilled in the TVZ geothermal fields, despite geothermal boreholes being drilled since 1958. Temperatures encountered at drilling depths (up to ~350°C at depth of ~3.5km) are too high for traditional borehole image tool technology (which commonly caps at ~175°C). The development of a borehole televiewer (BHTV) tool by the HIgh Temperature Instruments for supercritical geothermal reservoir characterization and exploitation (HITI) project [11], first deployed in New Zealand in 2009, provided the first acoustic borehole images of the TVZ subsurface. Since then other logging practises (well quenching while logging) have been tested in some New Zealand geothermal fields to allow the acquisition of resistivity borehole images, though these are still rare [12]. To date approximately thirty wells in six TVZ geothermal fields have had an image log acquired which has provided the first direct measurements of sub-surface fracture properties and horizontal stress field orientations within TVZ geothermal reservoir lithologies. This paper highlights some of the key research and findings on structurally controlled fluid flow in New Zealand geothermal fields that have been produced from analyses of a selection of these new datasets and how this information can provide further insight into larger questions around the architecture of the TVZ itself.

1.1. Geological setting

The TVZ (~350 km long, ~60 km wide) is an extensional, back-arc rift structure located in the North Island of New Zealand, which formed as a result of westward subduction of the Pacific Plate (Fig. 1). The TVZ has experienced >4Ma, NW-SE (~137) directed extension most of which is accommodated by active rift faults, the modern expression of which is referred to as the Taupo Fault Belt (TFB) [13, 14]. The TFB is dominated by NE-SW striking faults which show strong spatial polarity in dip direction (NW or SE) that is used to define the approximate positions of the rift axis [15]. Offsets along this inferred rift axis are present and have been described as accommodation zones rooted in NW-SE oriented basement structures which are thought to play a crucial role in the spatial distribution of TVZ geothermal fields [16].

NNW-SSE and NW-SE striking, greywacke basement faults in the TVZ are not directly observed but are inferred from gravity and magnetic data, landsat data, aerial photos, second order residual gravity anomalies, and field mapping of exposed greywacke basement outside the rift [17]. N-S trending structures are also defined within the TFB by topographical mapping and seismic interpretation, and are inferred to be reactivated basement fabrics [18, 19], report NW-SE, N-S and E-W structural fabrics from measurements of fault traces and joints across the TVZ and TFB.

TFB faulting is pure normal to normal with a small strike-slip component [20, 21]. The dominant NE-SW fault strike orientation, and focal mechanisms define a vertical stress component (σ_1; S_v), a NE-SW oriented maximum horizontal stress component (σ_2; S_{Hmax}), and a horizontal minimum stress component (σ_3; S_{hmin}) aligned approximately NW-SE across the TVZ consistent with the extensional setting of the region. Evidence of strike-slip faulting is inferred from a number of sources a) steepness of fault dips, b) en echelon geometry of faults, c) horsetail splaying of major NE-SW trending faults and, d) the intersection of the North Island Dextral Fault Belt (NIDFB) [15, 22], though active fault scarps in the TVZ show geomorphic evidence of strike-slip displacement of surface morphological features [20].

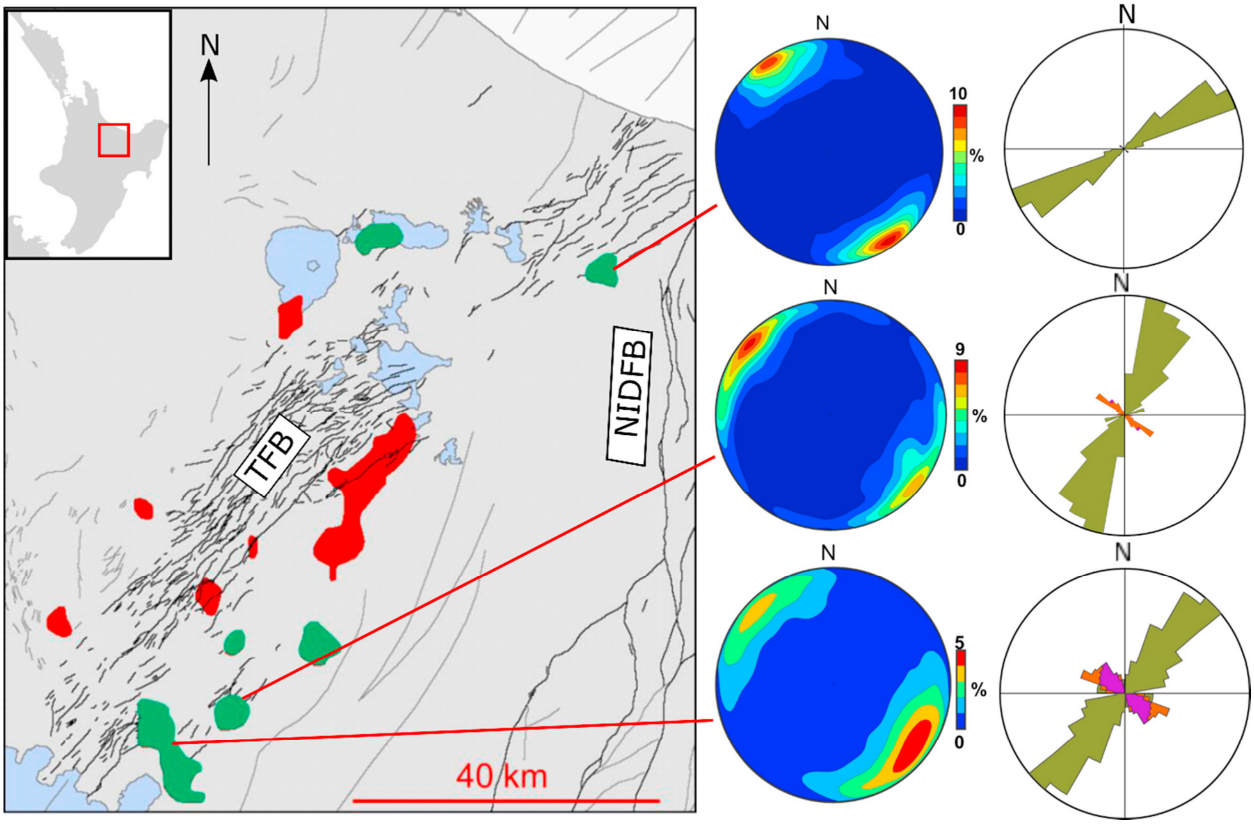

Fig. 1. Map of the Taupo Volcanic Zone showing geothermal fields (green = borehole images acquired, red = borehole images not acquired to date), active faults (dark grey lines). 1 = Taheke, 2 = Kawerau, 3 = Ohaaki, 4 = Ngatamariki, 5 = Rotokawa, 6 = Wairakei-Tauhara. TFB = Taupo Fault Belt, NIDFB = North Island Dextral Fault Belt. Fisher contoured, lower hemisphere stereonets showing fracture orientation distributions for all fractures measured in each of the Kawerau, Rotokawa, and Wairakei Geothermal Fields. Bidirectional rose diagrams showing in situ horizontal stress orientations for each of the Kawerau, Rotokawa, and Wairakei Geothermal Fields (Yellow = Drilling Induced Tensile Fracture/SHmax, Purple = Borehole Breakout/Shmin, Orange = Petal Centerline Fractures/Shmin).

2. The structural architecture of the TVZ geothermal subsurface

Of the well data investigated to date 13303 fractures (2032 in Kawerau, 5676 in Rotokawa, 5595 in Wairakei-Tauhara) have been manually picked the orientation of which is dominantly NE-SW striking, dipping steeply (>60°) both NW and SE (Fig. 2). Fracture orientations by geothermal field also display a dominant NE-SW strike orientation (Fig. 1). It is only when the individual geothermal field fracture data is investigated well by well that variations in the dominant structural trend start to become apparent. This was described in detail for the Rotokawa Geothermal Field [1, 23] where three wells worth of fracture orientation data (corrected for orientation sampling bias), collected mostly from within the Rotokawa andesite geothermal reservoir lithology, show distinctive differences in dominant fracture orientations. RK18L2 displayed NE-SW striking fractures that dominantly dipped SE and a subordinate N-S striking fracture set (dipping both E and W), RK32 shows a dominant NE-SW striking fracture set with a bimodal NW and SE dip direction pattern and a subordinate set of NW dipping fractures with shallower dip angles (~70°), and RK30L1 contains a NE-SW striking fracture set dipping mainly to the NW as well as a subordinate N-S striking fracture population (dipping both E and W). This orientation variability is attributed to each individual well's proximity to subsurface, km-scale, graben bounding faults inferred from 3D modelling [1, 4].

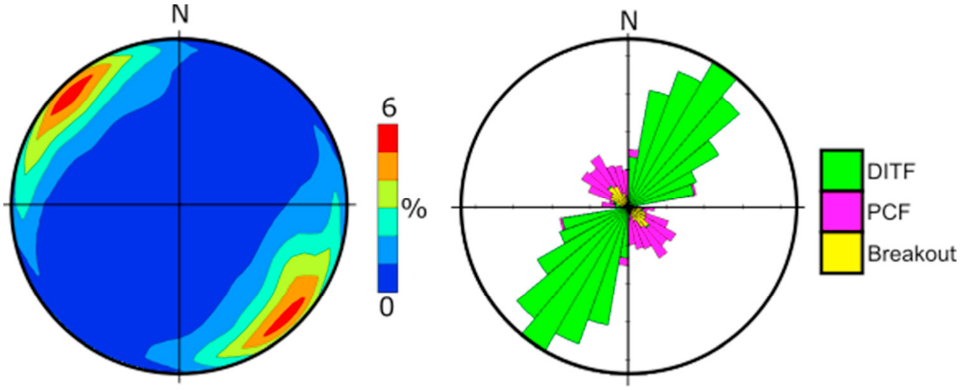

Fig. 2. a) Fisher contoured, lower hemisphere stereonet showing fracture orientation distributions for all fractures measured to date from BHTV logs in the TVZ (n=13303). b) Bidirectional rose diagrams showing in situ horizontal stress orientations made from stress induced features from BHTV logs in the TVZ (Yellow = DITF/S_{Hmax} (n=472), Purple = Borehole Breakout/S_{hmin} (n=82), Orange = PCF/S_{hmin} (n=127)).

Going a further level of scale down, to the individual well scale, in the Rotokawa dataset we see that again the dominant dip direction of the fractures varies. While an individual well may display a dominant fracture dip direction, discrete depth intervals (tens of meters) showed an antithetic dip orientation. These patterns can be taken to infer the potential occurrence of small scale antithetic faults associated with the larger scale faults implied to give each well its dominant fracture orientation (Fig. 3).

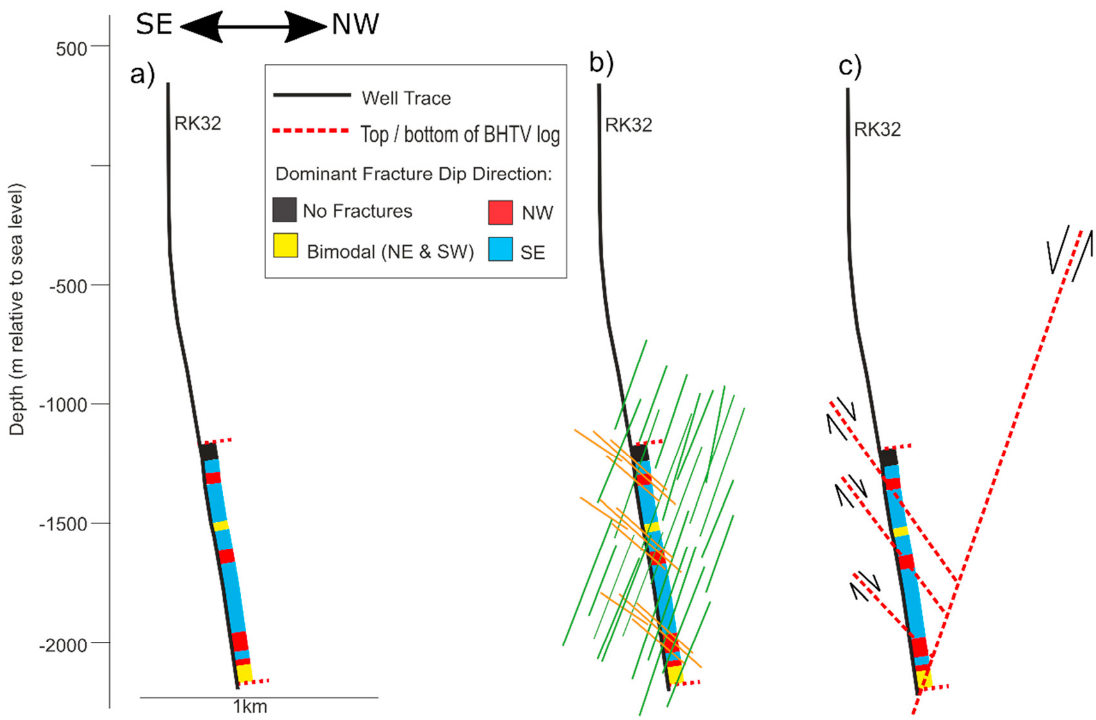

Fig. 3. a) Schematic cross-section of well RK32 from the Rotokawa Geothermal Field colored for dominant fracture dip direction. b) Well RK32 overlaid with the expected fracture patterns to be found in the rock mass being drilled into (Green = the dominant SE dipping fractures, Orange = the locally dominant NW dipping fractures). c) Inferred normal fault in proximity to well RK32 and suspected antithetic faults determined from the variable dominant fracture dip directions.

In the Kawerau Geothermal Field two image logs acquired in the basement greywacke geothermal reservoir reveal the expected dominant NE-SW striking fracture set. In addition, one well (PK8) also contains a small, subordinate fracture set with NW-SE striking fractures [25]. When examined in relation to the basement faults modelled for this field [26] it is shown that the PK8 well was drilled in proximity to the intersection of a large-scale NW-SE oriented fault and a NE-SW oriented fault [25]. It is determined that the well's proximity to the NW-SE striking fault is responsible for the higher occurrence of NW-SE striking fractures observed from the image log acquired in this well.

In the Wairakei Geothermal Field, once again variation in dominant fracture orientation trends are observed between different wells, though here the heterogeneity is found in variable dominant dip directions and in dominant fracture strike orientations [17, 27] (Fig. 4). While an overriding NE-SW strike orientation is readily apparent, there are wells that display a stronger E-W strike orientation (WK262, WK264, and WK123). The presence of this E-W strike fracture orientation may be related to the occurrence of E-W striking active faults that have been mapped at the surface in areas of the Wairakei Geothermal Field [28]. Linking the subsurface fracture orientations to larger subsurface structures is problematic given the complexity of the 3D modelled fault system and the uncertainty about how these modelled structures relate to the recorded active surface fault orientations.

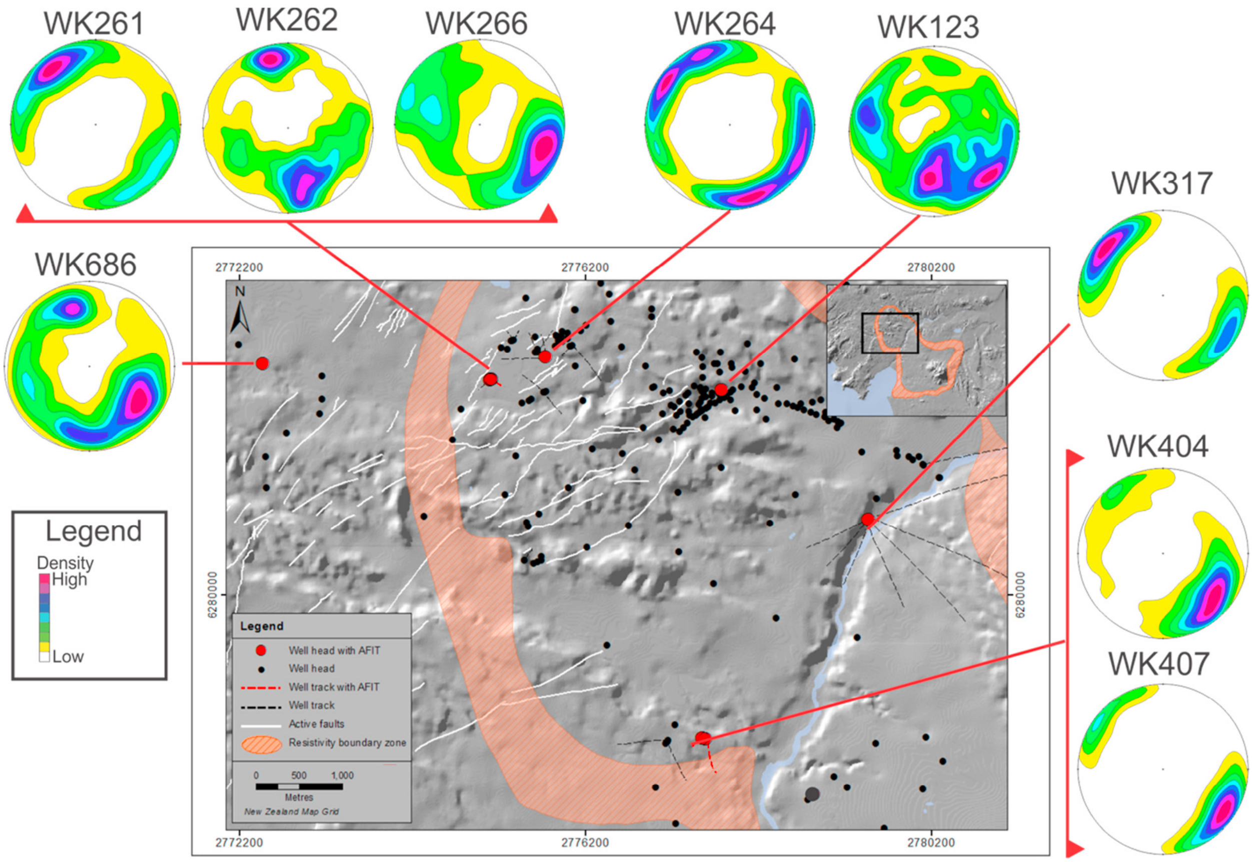

Fig. 4. Map of the Wairakei Geothermal Field showing Fisher contoured, lower hemisphere stereonets of poles to planes of structures identified from individual wells with an acquired BHTV log (Modified from [27]).

An alternative explanation for the variation noted in the dominant fracture orientations in the Wairakei Geothermal Field may be related to lithology. Fractures measured form borehole images in the Wairakei geothermal wells occur within a range of lithology types including variably welded pyroclastics (Wairakei Ignimbrite), volcaniclastics (Tahorakuri Formation, Waiora Formation), andesites, rhyolites, and sedimentary units (Waikora

Formation). When collated by lithology, further variations in dominant fracture orientation become apparent e.g. a N-S dominant fracture strike orientation in depth intervals inferred to be within the Wairakei Ignimbrite (Fig 5). Lithology is frequently linked to fractures development and propagation with physical property variations (strength, layer thickness, porosity, primary structural features) controlling a range of fracture attributes (length, aperture, orientation, and spacing) [29]. Within the Kawerau Geothermal Field detailed analysis of fracture aperture and orientation trends against greywacke to argillite composition trends from drill cuttings found that wider aperture fractures and more diverse fracture orientation patterns occurred within the greywacke sandstone rich intervals rather than the argillite rich ones, implying a mechanical strength control on fracture properties [25]. Discerning whether the fracture orientation patterns observed from borehole image logs are controlled by lithological properties, tectonics, or both requires much further detailed analysis of image log data in concert with available drill-core, and modelling of various fracture system generation processes.

The structural orientation data provided from TVZ borehole image logs is invaluable in developing the underpinning theories on the structural organization of the rift itself. For example, the Wairakei Geothermal Field is spatially located within an inferred accommodation zone (rift offset). Current theory suggests large-scale basement faults oriented NW-SE control the surface expressions of these rift offsets. From current analysis of the BHTV fracture data in the Wairakei Geothermal Field it is unclear whether NW-SE striking fractures (10% of the total dataset) in the top 1-3 km are an expression of a similar large-scale fault trend through the field or whether they developed as part of the connected network concurrent with the dominant NE-SW tectonic fracture trend [17]. Further, more detailed analysis of existing datasets, and acquisition of future borehole images in the TVZ geothermal field, will provide higher constraint on the potential structural organisation and location of the TVZ rift accommodation zones.

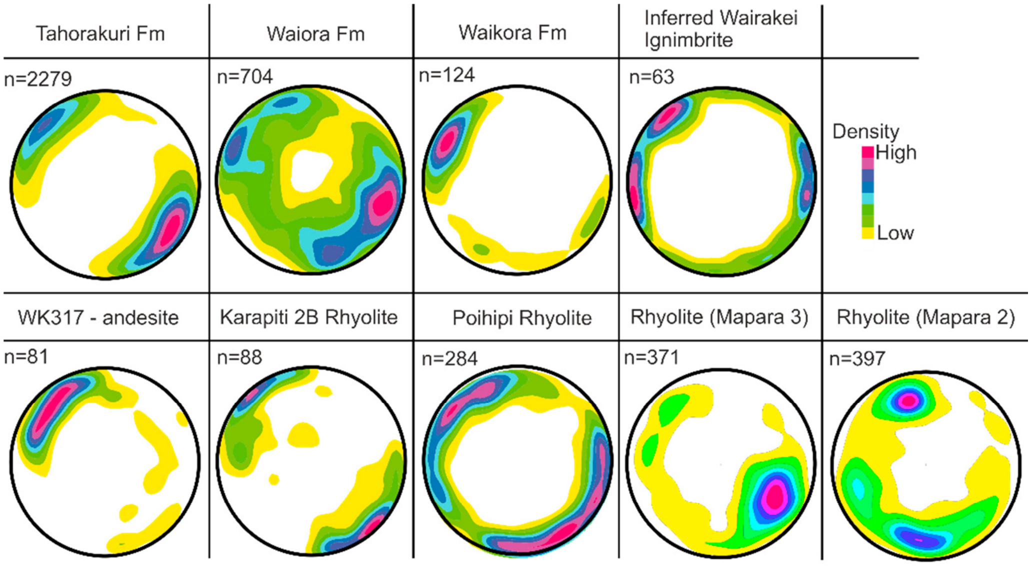

Fig. 5. Fisher contoured, lower hemisphere stereonets of poles to planes of structures identified within individual lithologies within the Wairakei Geothermal Field in which a BHTV log was acquired (from [17]).

3. Horizontal stress field orientations in TVZ geothermal fields

The advent of borehole imaging has provided the first indirect measurements of the horizontal stress field orientations in the geothermal fields of the TVZ. Features such as borehole breakouts, drilling induced tensile fractures (DITF), and petal centerline fractures (PCF) form around a borehole wall in response to far field stresses, providing indirect measurements of the orientation of S_{hmin} and S_{Hmax} [30, 31]. The most common stress induced features on the TVZ borehole images are DITFs and PCFs. Borehole breakouts are rare which is thought to be related to the thermal stresses acting on the borehole wall where cooler drilling fluids meet the hotter formation temperatures, creating a more tensile stress field around the borehole circumference [1].

As expected, the general trend of the data collected from TVZ borehole images logs (Fig. 2) is in agreement with the broadly defined NW-SE extension direction (S_{hmin}), discussed before, with the horizontal maximum stress direction (S_{Hmax}) aligned with the dominant structural strike trend (NE-SW). Variation in dominant stress field orientations becomes apparent though when you examine the data from each individual field (Fig. 1). The Wairakei Geothermal Field shows a S_{Hmax} orientation (~045°) consistent with the TVZ rift orientation, but the Rotokawa and Kawerau Geothermal Field shows rotations away from this NE-SW S_{Hmax} orientation towards ~015° and ~065° respectively. Possible explanations for the observed rotation of the horizontal stress field near Kawerau include; 1) the stress field near Kawerau is perturbed due to proximity to the strike-slip faulting of the NIDFB, 2) Kawerau lies just north of the Okataina Caldera which shows a deflection of the normal active faulting to a more E-W trend which may be mirrored by stress field orientations, 3) the wells from which stress measurements are made in the Rotokawa and Kawerau Geothermal Fields are located near active, large-scale faults which may have locally perturbed the stress fields orientations [1, 18, 24, 26].

Examination of the horizontal stress field orientations within individual TVZ geothermal fields reveals further variation. In the Rotokawa Geothermal Fields a difference of ~19°–24° in the mean S_{Hmax} direction between well RK18L2 and wells RK30L1 and RK32 is observed and thought to have resulted from the compartmentalization of the geothermal field into areas of different stress orientation regimes governed by large-scale NE-SW striking faults [1]. Similar well to well, field-scale variations in the horizontal stress field orientations can be seen from BHTV logs from Wairakei Geothermal Field boreholes [27].

When observed at the individual well-scale, the orientation of stress induced features on borehole images also show variability across discrete depth intervals (<10m) [1, 27]. These intervals, when examined closely, often show a change in the orientation of a DITF or borehole breakout as it moves across a single, or group, of natural fracture planes (Fig.6). This stress field orientation perturbation across discrete fractures is interpreted as a result of recent slip activity on these structures, and the identification of active sets of structures in the geothermal reservoir. The orientation of these recently active structures from the Rotokawa Geothermal Field shows a dominant NE-SW strike orientation which is consistent with the dominant strike orientation of TVZ active faults [1].

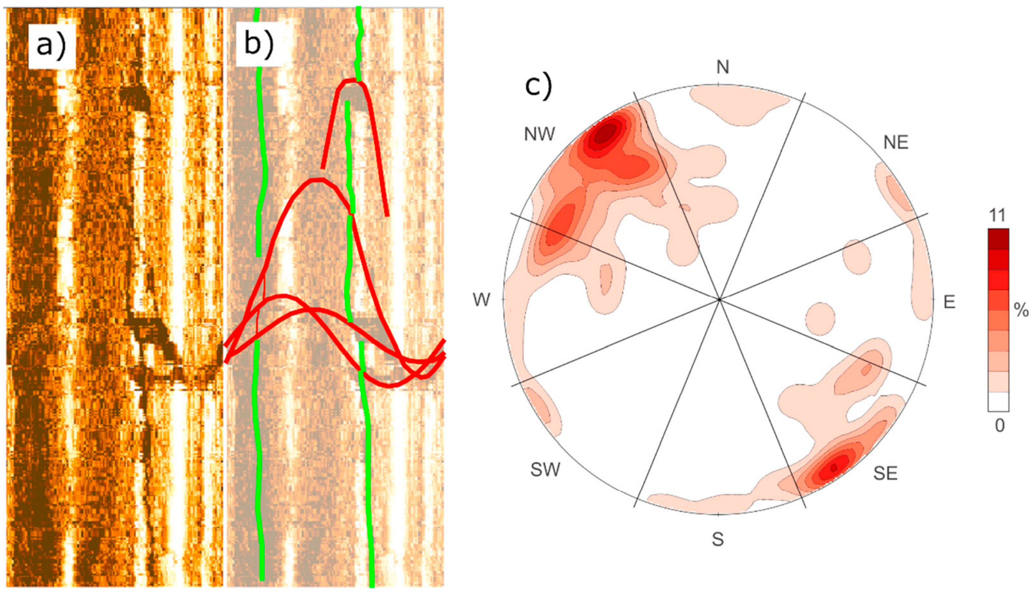

Fig. 6. Interval of dynamically normalized BHTV log from well RK32 showing DITF azimuth (green lines) changing across individual fracture planes (red lines), a) Imaged interval, b) Imaged interval with overlaid interpretation, c) Fisher contoured, lower hemisphere stereonet of pole to planes of fractures over which DITF orientation display a rotation of >10° in the Rotokawa Geothermal Field (from [1]).

4. Structurally controlled fluid Flow in TVZ geothermal fields

Geothermal reservoir permeability is controlled by a combination of multiple factors including intrinsic permeability, structure, stress, and reservoir mechanics [32], and fracture sealing and reservoir rock alteration [33, 34]. An expertly coupled thermochemical-mechanical understanding of a geothermal reservoir is required to understand how these factors operate in tandem and study of the borehole image logs from TVZ geothermal fields will go some way to realizing that.

While structure is considered a significant control on the convection of geothermal fluids throughout the TVZ there has been little direct observation of this. At the rift scale of the TVZ, inferred, intersecting (NW-SE and NE-SW striking), large-scale, basement faults are thought to provide vertical structural pathways for geothermal fluids to move upward and generate the geothermal fields of the TVZ [16]. At the geothermal field-scale, tracer test results [35], seismicity patterns [36, 37], and observations of trends in geothermal surface expressions [24] show the influence of structure on fluid migration in TVZ geothermal reservoirs by facilitating fluid flow along structural orientations consistent with the dominant structural trend (NE-SW), or by creating cross-fault fluid flow barriers.

Direct evidence for individual fluid flow in sub surface structures has now been brought to light by the combination of the structural data from borehole image logs and measurements of pressure, temperature, and fluid velocity (PTS logging). Direct observations between large aperture fractures and indicators of flow into and out of wells in the Wairakei Geothermal Field has been observed [38]. Similarly, in the Rotokawa Geothermal Field combined logging datasets reveal that fractures within fluid flow zones of the imaged wells were dominated by NE-SW strike orientations, and to a lesser degree E-W fracture strike orientations providing a number of orientations for good connectivity in these zones [1]. Further, detailed work is required to combine these data-sets so that all potential fracture related flow can be identified and characterised for use in conceptual and flow models for TVZ geothermal fields [39].

5. Conclusions

Borehole imaging in the geothermal fields of the TVZ has proven a valuable source of previously unobtainable data on the parameters of reservoir fracture properties (orientation, aperture, and density) and subsurface horizontal stress orientations. Fracture data acquired from borehole image logs augments structural measurements made via other methods from surface mapping to structural inferences from geophysical and modelling techniques. These rich fracture datasets provide insights into larger scale subsurface faulting architecture, and inputs for fluid flow modelling in geothermal reservoirs. Borehole image logging grants finer scale resolution on the stress state of the active TVZ rift by providing extensive data on horizontal stress orientations and perturbations. Given the intrinsic link between structure, stress, and fluid flow in geothermal reservoirs, borehole image logging in the TVZ provides a good base for developing fully realised geomechanical models of these resources in the future.

Acknowledgements

Acknowledgements to the ‘Geothermal Resources of New Zealand’ research program at GNS Science for funding this work. The authors would also like to acknowledge Contact Energy Ltd., and the Rotokawa Joint Venture Ltd. (Mercury Energy and Tauhara North No. 2 Trust) for the acquisition of borehole image logs in their respective resources and for providing access to the data that informed many of the original studies discussed in this paper.

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