QUANTIFYING THE STRESS DISTRIBUTION AT THE ROTOKAWA GEOTHERMAL FIELD, NEW ZEALAND

Jonathan Davidson[1], Paul Siratovich[1], Irene Wallis[2], Darren Gravley[1]and David McNamara[3]

[11]Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

[2] Mighty River Power, Rotorua, New Zealand

[3]GNS Sciences, Wairakei, New Zealand

jrjdavidson@gmail.com

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ABSTRACT

Knowledge of the orientation and magnitude of the principal stresses can be used to model the behavior of faults and fractures, and determine how they may influence fracture hosted permeability in geothermal reservoirs. The permeability of the Rotokawa geothermal reservoir is dominantly fracture hosted and tectonic stresses are largely responsible for maintaining fluid flow in the reservoir. Reactivation of a fault or fracture depends on its orientation relative to the orientation of the stress field and the magnitude of the principle stresses. The purpose of this study is to determine the magnitude of the three principal stress axes at Rotokawa, and how they vary spatially. This will help our understanding of the distribution of fracture-hosted permeability in the reservoir.

In the extensional tectonic settings, such as the Taupo Volcanic Zone, the magnitude of the vertical stress is dominated by the weight of the overburden. Previous rock density studies on core from Rotokawa wells and on rock from other geothermal fields are used here, along with variable thicknesses of different geologic units, to model the vertical stress. Leak-off tests and acoustic images that contain stress induced features are used to quantify aspects of the minimum and maximum horizontal stresses. We show that the differential stress between the vertical and minimum horizontal is near the threshold for frictional failure. More importantly, preliminary results of our study indicate that spatial variation in the vertical stress magnitude may be an important factor in fracture permeability. This study highlights some of the difficulties faced when attempting to estimate stress magnitudes in a geothermal reservoir hosted in a complex volcanic terrain.

1. INTRODUCTION

The Rotokawa Geothermal Field is located about 10 km northeast of Taupo Township, in the eastern part of the Taupo Volcanic Zone (TVZ). The TVZ geology is dominated by Quaternary volcanism deposited on top of the Mesozoic 'greywacke', (Rae, 2007). The TVZ has been undergoing volcanism since 2 Ma, and has been actively rifting since at least 0.9 Ma(Wilson et al., 1995). The maximum principal stress in an extensional setting is vertical (Anderson, 1951) and seismic studies confirm this in the TVZ (Hurst et al., 2002).

The Rotokawa hydrothermal system is divided into three distinct levels separated by impermeable formation: a hot geothermal reservoir; an intermediate aquifer; and a shallow aquifer (Sewell et al., 2012). The permeability of the reservoir rocks at Rotokawa is dominated by faulting and fracturing of host rocks (Rae, 2007).

Barton et al. (1995) showed that fractures open to fluid flow in crystalline rock tend to have a shear stress to normal stress ratio greater than 0.6. This ratio of 0.6 is similar to that derived experimentally for the friction of common crustal rocks (Byerlee, 1978). The fact that friction is a major contributor to fracture permeability implies that the main mechanism that keeps fractures open to fluid flow is slip.

The amount of shear and normal stress imposed on fractures is dependent on: (1) the orientation of the fractures with respect to the orientation of the principal stress axes; (2) the relative magnitude of the principal stresses; and (3) pore pressure. Studies of acoustic images in TVZ wellbores seem to support this observation. Fractures thought to be permeable have a restricted range of orientations with regards to the in-situ stress field (McLean and McNamara, 2010; Wallis et al., 2012). In order to model which fracture orientations are likely to experience slip, we attempt herein to quantify the magnitude of the three principal stresses at Rotokawa Geothermal Field.

2. METHODOLOGY AND RESULTS

2.1 Vertical Stress

We make the standard assumption that the vertical stress is entirely dependent on the weight of the overburden, as the surface of the Earth acts a free surface that cannot sustain shear stress. This assumption is generally supported by data from underground excavations (Brown and Hoek, 1978). The magnitude of the vertical stress is given by the following integral:

$$S_v = \int_0^z \rho(z) g dz \,,$$

where g(m/s^2) is the gravitational constant and ρ (kg/m^3) is the density at depth z(m). In this paper, stress is defined as positive in compression

The shallow rock units in the TVZ (<1.5 km) exhibit a wide range of densities (Stern, 1986). If the rocks are separated into geological units however, it can be shown that the range of densities of each unit is small, even when comparing a range of altered and unaltered rocks (Pochee, 2010). Figure 1 depicts the density ranges for some of the

geological units that occur at the Rotokawa Geothermal Field.

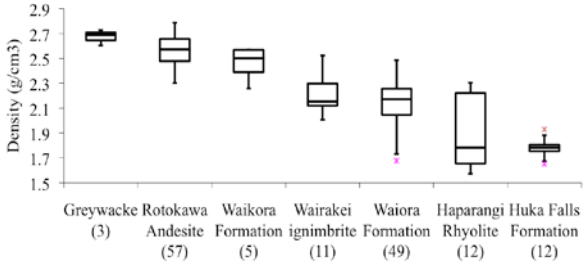

Fig. 1: Box plot of density measurements of core. Geological units shown are known to occur at depth at the Rotokawa Geothermal Field (number of measurements in brackets). Data from Pochee, 2010; Siratovich et al., 2012; Mielke, 2009; Whitford and Lumb, 1978.

To compute the vertical stress at Rotokawa we integrated the average saturated density of each geological unit with respect to the known thicknesses of each unit as derived from well data. This method does not take into account the deviation of wells. In some cases this means that where there is a sharp lateral variation in unit thickness, the model may not yield the true weight of the overburden. A 3-dimensional geological model will be used to estimate the vertical stress in order to avoid this problem in the next phase of our study.

Where density data was absent, we used values from a similar geological unit in order to estimate the vertical stress. An interpreted natural state pressure profile for the Rotokawa reservoir is employed in this overburden calculation. The results of the model for each well in the Rotokawa field are shown in Figure 2.

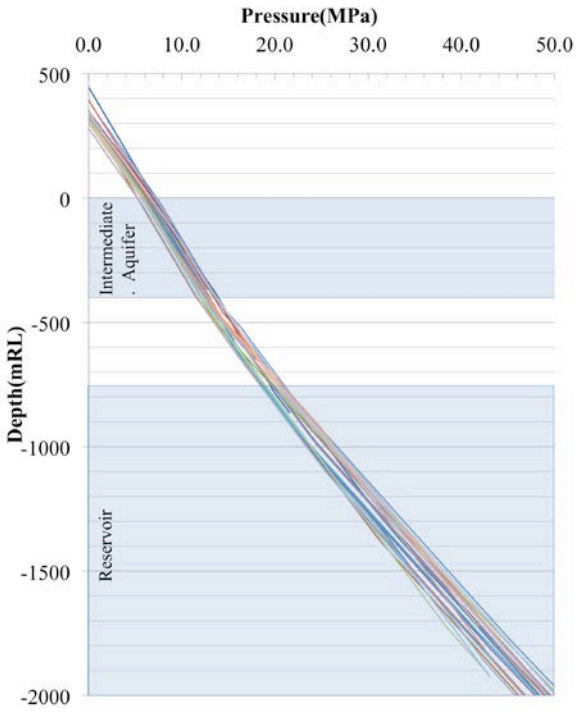

Fig. 2: Vertical stress model for wells in the Rotokawa Geothermal Field. The reference level (RL) is the sea level.

The results from the vertical stress model shows that the effect of varying thickness of geological units has as great an impact on the vertical stress as topography does. For example: The well drilled from the highest elevation (highest RL) is expected to have the highest vertical stress at depth. However, that well has a modeled vertical stress profile several MPa lower than other wells drilled from a lower elevation. This is due to the presence of thick, low-density formations present under the well drilled from a high elevation.(try to distinguish high elevation well in figure 2)

Furthermore, the difference between the highest and lowest vertical stress modeled at sea level is 2.4 MPa, where most of the divergence between wells would be caused by topography. The difference at -1500 mRL is 5.1 MPa. This divergence is caused by a variation in rock density across the field. Both of these observations support the hypothesis that thick, low-density formations may affect the vertical stress at depth.

There are several shortcomings of this for modeling the vertical stress. Fractures, brecciation, and voids would cause the overall density of the rocks to be lower than that measured by laboratory testing (Figure 1). This means that our results may overestimate the vertical stress. Also, the integration method described above may be oversimplifying the effect of differential loading due to topography or variations in density. Others have shown that a 'Boussinesq-type' approach for modeling vertical stress (which takes into account the lateral spread of the increased load at depth) would be more accurate (e.g., (Shea-Albin et al., 1992). We plan to investigate this method to improve our model in the future.

Although most units have a near normal distribution of density measurements (Figure 1), the Haparangi Rhyolite does not. This unit has a bimodal distribution of density data. This may be due to two different flow units within the rhyolite which have differences in vesicularity or pumice content. Given that the term "Haparangi" has been used in the past to define any type of rhyolite in the TVZ (Cole, J. pers. comms., 2012), it is quite likely that this unit consists of more than one geologic or stratigraphic member. Using the mean of the density for the whole population might not reflect the true vertical stress caused by the overburden weight of this unit, or any other unit that has a similar variation in density.

Further work is required to refine which density measurements will be applied in the overburden model and to test the effect of topography. However, it is likely that these factors will have little influence on the overall final overburden model. The version presented here represents a good approximation of the true vertical stress.

2.2 Minimum Horizontal Stress

A number of empirical formulae have been developed to estimate minimum stress (e.g., Hubbert and Willis, 1957 & Soback and Healy, 1984), however these are location specific (i.e., they only accurately model the locations for which they were developed; Bourgoyne et al., 1986).

Alternatively, in-situ methods can be used to measure the magnitude of the minimum horizontal stress while drilling; these are known as Leak-off Tests (LOTs). LOTs are conducted regularly in geothermal wells in order to calculate the "fracture gradient". This gradient is used by drilling engineers to design well casing and to set safe pressure operating limits particularly in well control situations. A LOT involves drilling a few meters into a rock formation after setting a casing shoe, pumping water into the well at a slow rate and monitoring the pressure change. If a fracture forms, the pressure will drop or plateau, as water escapes from the well into the rock formation. Following fracture formation, a set amount of water is pumped before the well is shut in and the pressure decline is monitored.

Not all LOTs conducted at Rotokawa were successful in creating fractures. As fracture creation is essential to deducing the minimum principal stress magnitude, we attempted to differentiate between types of tests using the differential of pressure with respect to time (dP/dt) plotted against the pressure (Song et al., 2001).

Out of the 41 LOTs surveyed here, 12 tests did not use a constant pumping rate, making determination of the minimum principal stress from these tests problematic. Eighteen tests did not show a clear fracture opening, as they showed a linear relationship between dP/dt and P. The flow rate from the wellbore into the formation during these tests is dependant on the difference in pressure between the pore fluids and the wellbore fluids. This relationship fits with Darcy's law for flow of a fluid through a porous medium. The fluid pressure in these tests did not overcome the tensile strength of the rock to form a fracture, but instead the fluid leaked into the formation by taking advantage of the existing permeability. These tests cannot be used for stress measurements.

Eleven LOTs did show fracture opening, denoted by a sharp change in the dP/dt relationship. Most of these tests also showed a sharp drop in pressure. This drop can only be accounted for by an increase in the downhole volume occupied by the fluid, implying the formation of an open fracture. We assume that all of these tests propagated fractures beyond the disturbance of the stress field caused by the presence of the borehole. The Fracture Closure Pressure (FCP, the pressure at which the fracture closes again) was used as an equivalent to the magnitude of the minimum principal stress. The method we used to determine the FCP is the double tangent method (White et al., 2002; Fjar et al., 2008).

The FCPs of the LOTs that opened fractures are plotted against the depth at which they were measured (Figure 3). The black dashed line shows the magnitude of the minimum horizontal stress, for which optimally oriented fractures would slip, using a coefficient of internal friction of 0.6 (Jaeger and Cook, 1969). Out of the 11 LOTs that showed fracture opening, 10 minimum horizontal stress magnitudes are either close to frictional equilibrium (plotting just higher than the black dashed line) or critically stressed (plotting lower).

The FCP of one test measured in the Waiora Formation suggests a minimum horizontal stress magnitude much greater than expected at that depth (if we assume the stress in the crust was near frictional equilibrium). This test did not show a pressure drop after the opening of the fracture. Since this test is not creating new fracture, which would be the case if a pressure drop was observed, we suggest that, instead, a pre-existing, mis-oriented fracture has re-opened allowing fluids to escape. A mis-oriented fracture is one whose plane is not orthogonal to the direction of the minimum principal stress, and would require a higher pressure to remain open. This scenario is feasible providing the fracture opening pressure for the mis-oriented fracture is low enough that the pressure of the fluids does not exceed the tensile strength of the rock. In this case, the FCP is not necessarily an estimate of the minimum horizontal stress.

In summary, we have rigorously differentiated the LOTs, identified those that provide an estimate of the minimum principal stress. Our findings are consistent with a crust at or near frictional equilibrium, in agreement with observations compiled by Townend and Zoback (2000). Our measurements are an estimate of the local minimum stress magnitudes. The true value of the minimum horizontal stress is likely to vary spatially.

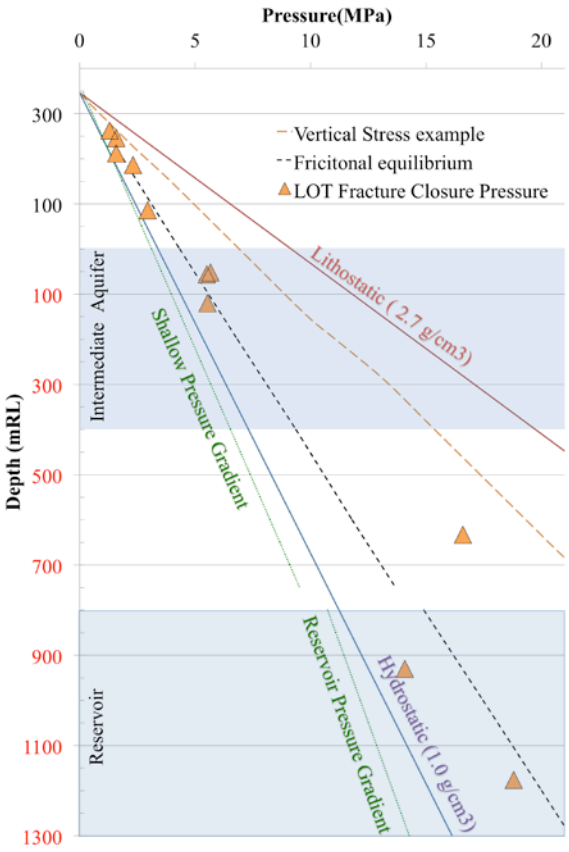

Fig. 3: Fracture closure pressure, overburden weight, and Rotokawa pore pressure (provided by MRP) plotted against depth. Lithostatic (ρ=2.7) and hydrostatic (ρ=1.0) pressure gradients have been plotted for reference.

2.3 Maximum Horizontal Stress

The magnitude of the maximum horizontal stress can influence which fractures are likely to be open to fluid flow (Barton et al., 1995), and therefore is an important factor in understanding permeability. However, the maximum horizontal stress magnitude is the most difficult of the stress axes to constrain.

The most common method for determining the magnitude of the maximum horizontal stress uses the width of borehole breakouts. Borehole breakouts are rarely observed from acoustic images at Rotokawa (e.g., Massiot and McNamara, 2011), and therefore this method cannot be applied here.

Another method makes use of the presence of drilling induced tensile fractures (DITF) in the borehole (Moos and Zoback, 1990). Under certain stress conditions, the borehole wall rock will experience tension and DITFs are formed. The presence of DITFs can be used to infer the stress conditions that led to their formation, and this can yield information on the magnitude of the maximum horizontal stress .

Three boreholes have been imaged at the Rotokawa geothermal field using an acoustic imaging tool and DITFs are a common feature observed on these borehole walls (Massiot and McNamara, 2011). Therefore it is appropriate to investigate the stress conditions around the borehole in order to understand how the DITFs formed.

As all the wells imaged at Rotokawa are deviated, we model the effect on the stress field caused by drilling the borehole using a method describing stress around a deviated wellbore (Peska and Zoback, 1995). We also take into account contraction caused by cooling of the wellbore during drilling. For this, we used the method described by Stephens and Voight (1982).

Figure 4 shows the stress conditions for which the borehole wall goes into tension, for the depth and orientations at which DITFs are observed in the acoustic images. Due to a lack of real constraint on the minimum horizontal stress magnitude at depths where DITFs are observed (no LOTs data), we modeled for every possible value of both horizontal stresses up to the assumed value of the vertical stress. The parameters used in this figure are summarized in Table 1. The range of temperature changes, ΔT, is derived from the expected differences between the temperature of the formation rocks and the temperature of the drilling mud. Values for the rock properties used in Table 1 are sourced from Siratovich et al. (2012).

Vertical stress	35.9 MPa
Pore pressure	16.14 MPa
Well Azimuth	355º
Well Deviation	22.5º
Drilling mud temperature	70º C
Maximum formation temperature	350º C
Minimum formation temperature	170º C
Range of ΔT	100º - 290º
Coefficient of thermal expansion	5.00 x 10^{-6} K^{-1}
Youngs modulus	29.5 GPa
Poissons ratio	0.21
Range in tensile strength	15.3 MPa - 24.2 MPa

Table 1: Summary of parameters used in Figure 4

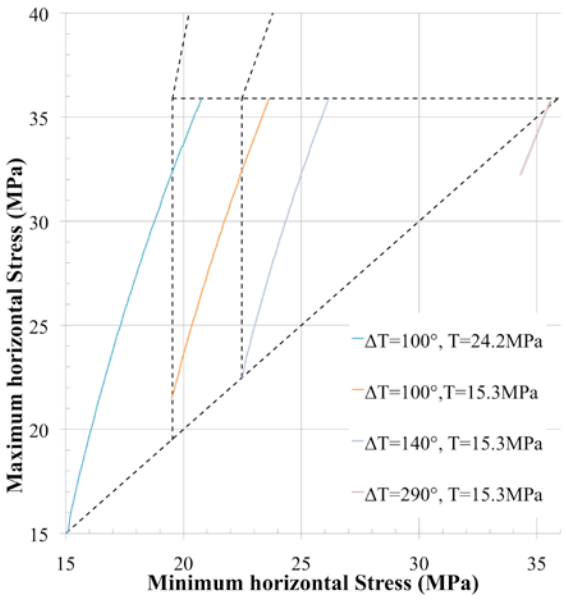

Fig. 4: Maximum horizontal stress vs minimum horizontal stress at a given depth where DITFs are known to occur. The coloured lines are plotted at the stress conditions required for the wellbore to go into tension, for various cooling temperatures (ΔT) and tensile strength (T).

The DITF model (Figure 4) shows that cooling of the formation rock by drilling fluids is a major factor in creating DITFs. Another important factor influencing the formation of DITFS is the tensile strength of the rock. The variability in the tensile strength of the Rotokawa andesite formation is large enough (Siratovich et al., 2012) to influence whether or not DTIFs will form.

This modeling indicates that we do not have sufficient constraint on the degree of cooling, or on the mechanical properties, of the rock to estimate the magnitude of the maximum horizontal stress. However, for an extensional setting, it is safe to assume that the magnitude of the maximum horizontal stress must be between the magnitude of the minimum horizontal stress and the vertical stress(Anderson, 1951).

3. DISCUSSION

The aim of this study was to quantify the magnitude of the stress axes in the Rotokawa geothermal field. We were able to build a model of the magnitude of the vertical stress, as a function of depth, based on the weight of the overburden. The magnitude of the minimum horizontal stress was inferred at specific locations in the field using LOTs.

What follows is a discussion of the uncertainty of the results, the expected temporal variation of stress during the lifetime of the production of a geothermal reservoir, and finally the expected orientation of permeable fractures inferred from these results.

3.1 Variation of total stress magnitudes over time

An important factor is the rate at which stress magnitudes might change in the Rotokawa geothermal field. Assuming that vertical stress is largely dependent on the weight of the overburden, vertical stress would then be sensitive to the addition or removal of rock material, or to changes in the

overall density of the geologic formations. Processes such as erosion, deposition and faulting could add or remove material. Processes that could change the density of the formation rocks, include (1) alteration (via mineral precipitation and dissolution) that change the porosity of the rock (Pochee, 2010; Powell, 2011) and (2) the creation or destruction of void space in fractures through fault slip. Most of these processes are thought to occur at time scales slower than the productive lifetime of the reservoir, and therefore the variation would be insignificant to this study.

The horizontal stress magnitude could also vary over time. The magnitude of stress is limited by the frictional strength of the crust and may be regularly perturbed by seismic events (Townend, 2006). It is also possible that aseismic creep could affect the magnitude of the total horizontal stress.

The Rotokawa geothermal field is located in a tectonically active region, and microseismicity has been observed in the geothermal field (Bannister and Sherburn, 2007); Thus, intermittent stress relief associated with fault slip is expected.

A detailed study of the orientation of the stress field at the Coso geothermal field shows that there is a significant variability in the orientation of horizontal stresses over short distances in geothermal fields; these variations could be caused by slip on faults (Blake and Davatzes, 2011). The heterogeneity in the orientation of horizontal stresses observed at Coso suggests that, in addition to orientation, fault slip might also cause significant variation in the magnitude of the horizontal stress at Rotokawa.

It may be possible to quantify the total stress drop caused by seismicity. In some seismically active areas, it has been proposed that the stress drop is proportional to the earthquake magnitude, for smaller (<3.5M) magnitude events (Sacks and Rydelek, 1995; Gibowicz et al., 1991; Abercrombie and Leary, 1993). If a similar relationship were true for Rotokawa, then stress drops due to microseismicity might be investigated using existing microseimic data.

3.2 Effect of pore pressure on fracture permeability

Pore pressure acts to reduce the normal stress according to the effective pressure law (Hubbert and Rubey, 1959). It follows that slip on fractures is strongly controlled by pore pressure through a reduction in effective normal stress.

The fluid pressure gradient data used here was developed from wellbore modeling and integrated across multiple wells in the field. In order to fit the results of this modeling, two gradients are required for Rotokawa(see Figure 3): one for the reservoir and one for the intermediate aquifer and lithologies above (Quinao, J. pers. comm., 2012).

The effect of pore pressure on fracture permeability would be just as great, or perhaps even greater than any variation in the total stress component, since pore pressure affects the effective normal stress of a fracture regardless of its orientation. No significant overpressures are noted at Rotokawa; in fact, the high thermal gradient of the geothermal system produces a pore pressure gradient that is sub-hydrostatic. It is possible that transient overpressures exist locally due to mineralization plugging fluid pathways. Pressure highs also exist in an operational reservoir in the vicinity of injection wells just as bowls of low pressure form in the vicinity of production wells. However, the lack of evidence of significant overpressure in the natural state suggests that pore pressure plays a minor role in the orientation of permeable fractures at Rotokawa.

3.3 Effect of differential loading on fracture permeability

The lateral variation in density across the field will affect the vertical stress at a given point. This variation in turn will impact on the population of fractures in the reservoir that are open to fluid flow (see Figures 6 and 7).

Figure 5 depicts the vertical stress as a function of depth for two wells with similar wellhead elevations, but sited in different sectors of the field. Each well intercepts a significantly different stratigraphy. As described in Section 2.1, density data is limited and calculations may not represent the true vertical stress magnitude. In order to convey this uncertainty, a range of "realistic", vertical stress profiles are computed for each well. These are derived from the 95% confidence limits on the mean formation densities (Figure 1) and assume that the populations are normally distributed.

There is some overlap in the range of vertical stress for the two wells due to the uncertainty in formation densities. However, results suggest that for a given depth, the difference in the vertical stress between the well in the NE field and that in the SW field area could be up to several MPa, a phenomena entirely due to differential loading.

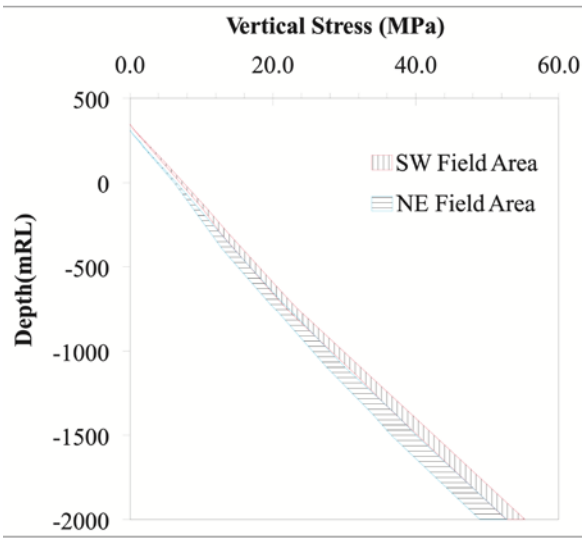

Fig. 5: Likely vertical stress range for two locations.

3.4 Shear and normal stress imposed on fractures

As mentioned previously, repeated slip helps keep fractures open to fluid flow. We use the magnitudes of minimum horizontal and vertical stresses derived in this study(see Figure 3) to estimate the normal and shear stresses that could act on fractures of a given orientation.

Mohr Circles are an effective way of displaying the shear and normal stresses imposed on fractures. The Mohr circles in Figures 6 and 7 are two-dimensional, such that they are only showing the maximum possible shear stress imposed on fractures. They are plotted for depths at which LOTs

have opened fractures. The smaller (red) Mohr circle was constructed using the lower estimate of vertical stress and the larger (blue) using the greater estimate (see Section 3.3). These plots illustrate the effect of variation in vertical stress caused by differential loading, on normal and shear stresses. The area that plots above the 0.6-shear/normal ratio represents the strike orientations of fractures likely to slip.

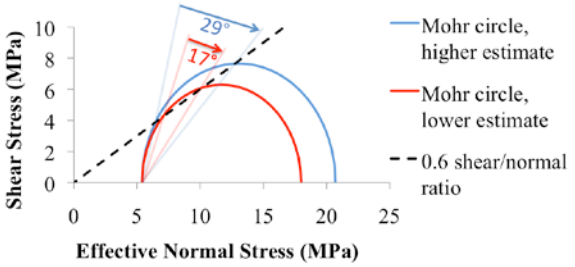

Fig. 6: Mohr Circle for stress estimation in the Rotokawa andesite at -1176mRL. The range of fractures with shear/normal stress above 0.6 is shown for both the lower and higher estimate of vertical stress. A variation in the vertical stress halves the range of fracture orientations likely to experience slip.

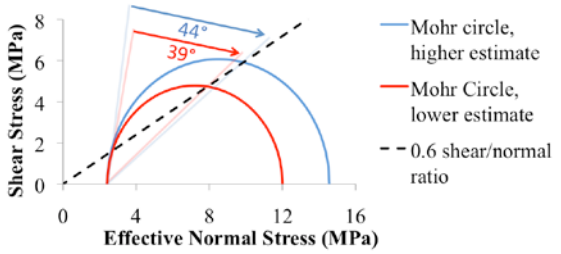

Fig. 7: Mohr Circle for stress estimation magnitude in the Wairakei ignimbrite at -930mRL. A variation of the vertical stress has little effect on the range of fracture orientation above 0.6 at this depth.

In both examples, a significant portion of fracture orientations plots above the 0.6 ratio. This suggests that quite a few fracture orientations might be open to fluid flow. A larger vertical stress results in a wider range of fracture orientations above the 0.6 ratio. The exact range of orientations of fractures above 0.6 depends on the magnitude of the maximum horizontal stress (see Section 3.5).

3.5 Effect of the maximum horizontal stress on the orientation of permeable fractures

Although we have not been able to constrain the maximum horizontal stress through modeling methods, we do know that its magnitude in an extensional tectonic setting must be between the minimum horizontal and vertical stress magnitudes (Anderson, 1951).

The stereonet in Figure 8 shows the range of fracture plane poles which (when under the vertical and minimum horizontal stress magnitudes estimated at -1176 mRL and for various magnitudes of the maximum horizontal stress) will have a shear to normal stress ratio higher than 0.6 (i.e., are likely to experience slip). The stress ratio ν in 3D is given by:

$$\nu = (S_1-S_2)/(S_1-S_3),$$

where S_1, S_2, and S_3 are the magnitudes of the vertical, maximum horizontal, and minimum horizontal stress respectively.

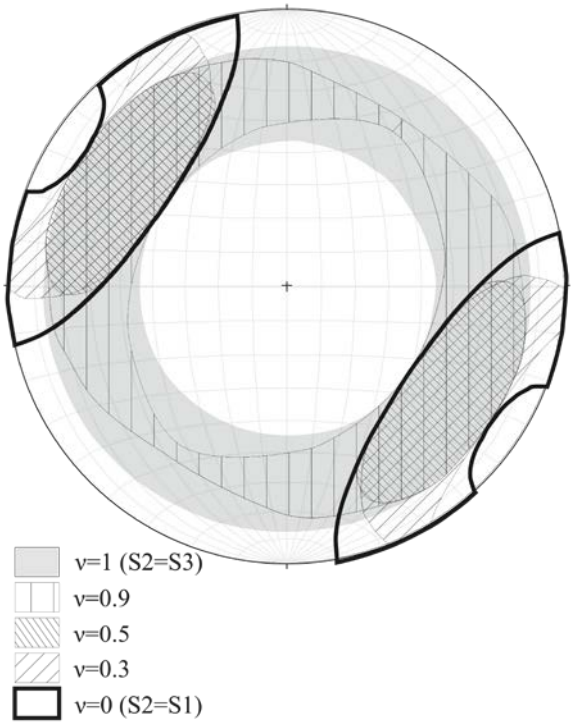

Fig. 8: Equal-area lower hemisphere stereonet (Allmendinger et al., 2012) with shaded regions representing poles of fractures with a shear/normal stress ratio above 0.6, for stress conditions similar to those at -1176mRL, using the higher estimate of vertical stress. Different shadings represent different magnitudes of the maximum horizontal stress. Orientation of minimum horizontal stress ~124°.

The stereonet in Figure 8 shows that the maximum horizontal stress controls the orientation of fractures that will have shear/normal stress ratio greater than 0.6. Where S2=S3 (ν=1), the fracture strike orientations likely to experience re-shear is unconstrained. The range of fracture orientations that are likely to experience slip is smallest in the case where ν = ~0.5.

The effect of changing vertical stress is significant. For the lower possible value of vertical stress given in Figure 6, the range of fractures with a ratio above 0.6 is reduced to a narrow range for all values of ν except for ν = 0 or 1.

If we assume that the reservoir rock has pre-existing fractures that are randomly oriented, then for a given vertical and minimum horizontal stresses, the orientation of fractures that are open to fluid flow is strongly controlled by the maximum horizontal. Understanding what affects the

maximum horizontal stress in a reservoir may be the key to understanding its permeability.

4. CONCLUSION

Our study attempts to quantify and model the magnitudes of the three principle stresses at Rotokawa. A number of challenges were encountered during model construction including: a scarcity of valid measurements of the minimum horizontal stress; a complicated overburden; and insufficient information to constrain the maximum horizontal stress. During model construction we found:

(1) The overburden model in a volcanic and volcaniclastic terrain contains more uncertainty than those constructed for sedimentary basins due to the inherent variation in the density of volcanic rock. However, we have shown that at Rotokawa the density variation between stratigraphic units is greater than within. A better understanding of rock density variation, such as density profiles from wireline logging, would improve the accuracy of our vertical stress model.

(2) The pressure gradient in a geothermal system is affected by the decrease in fluid density at high temperatures, such that the pressure gradient in the reservoir proper is sub-hydrostatic. This will influence the stress model and care must be taken to consider this when modeling a geothermal system.

(3) Leak-off testing in a naturally fractured reservoir does not always form new fractures. However, opening of existing fractures by increased pressurization during a LOT should still provide a reasonable approximation of the minimum horizontal stress provided the fracture is normal to the minimum principal stress direction.

(4) Simple two-dimensional Mohr circles have been used to demonstrate the impact uncertainty in the overburden model has on hydraulically conductive fracture orientation. However, to precisely quantify the fracture population that will be orientated for re-shear at Rotokawa, the magnitude of the maximum horizontal stress must be constrained and the fracture planes assessed in three dimensions.

(5) Standard methods of modeling the maximum horizontal stress have not constrained this principal stress beyond the range that can be defined by theory alone. This is because thermal effects at the wellbore wall have not been sufficiently quantified, and the range of mechanical properties of the rocks is too great.

Future work will build on the model presented here. We will investigate different techniques to improve the vertical stress model in 3 dimensions and will attempt to correlate between the vertical stress variation and the magnitude of the minimum horizontal stress. We will also try to assess the cooling that was experienced by the wellbore in order to constrain the maximum horizontal stress further. If successful, this work may lead to a better understanding of the location and orientation of permeability in the Rotokawa Geothermal Field.

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