Deformation, Strength, and Failure Mode of Deep Geothermal Reservoir Rocks

Paul A. Siratovich[1], Marlène C. Villeneuve[2], Michael J. Heap[3], Ben M. Kennedy[2]

[1] Mighty River Power, PO Box 245, Rotorua, New Zealand 3040

[2]University of Canterbury, Private Bag 4800 Christchurch, New Zealand 8140

[3]Université de Strasbourg/EOST, 5 rue René Descartes 67084 Strasbourg cedex France

paul.siratovich@mightyriver.co.nz

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ABSTRACT

Rocks sourced from active geothermal systems can have unique responses to deformation, due to unique alteration mineralogy and complex microstructure. The current state of understanding of mechanical behaviour of rocks under varying stress conditions is well established on suites of rocks with simple mineralogy and microstructure. Brittle failure can increase porosity and permeability and generate seismicity, whereas inelastic deformation in the ductile regime will decrease porosity and will likely decrease permeability, and generate no or distinct low frequency seismicity. Many studies have focused on the behaviour of siliclastic and carbonate rocks to establish the transition form brittle to ductile behaviour. The geothermal systems in New Zealand, and many other areas, are hosted in mainly volcanic rocks, limiting the applicability of current data and knowledge to these systems.

We present results from laboratory triaxial deformation and strength testing of drill core sampled from a deep geothermal reservoir. We have used our findings to construct failure criteria based on our investigations and compared them to the in-situ and induced stress conditions that may lead to macroscopically brittle or ductile deformation of the host rock. Our results show that under the current stress conditions at the Rotokawa geothermal field the host rock behaves in a brittle, rather than compactive, fashion. Under these in-situ stress conditions brittle fracture generation dominates over cataclastic pore collapse, resulting in a rock mass with suitable macro-scale permeability for fluid extraction. Our results also show that the rock strength is typically too high for the induced stresses during drilling to initiate borehole breakout. This is supported by borehole observations revealing very little borehole damage in the host rock.

1. INTRODUCTION

Constraining the behaviour of a rock under differential stress is of crucial importance to understanding how a changing stress field may result in the failure of a rock mass. High temperature geothermal reservoirs are prone to dynamic stress changes (Grant and Bixley 2011). In an actively utilized geothermal reservoir, the response of the stress field to extraction and reinjection of reservoir fluids affect the longevity of the resource. Through fluid extraction, pore pressure can be decreased, leading to an increase in effective pressure. This may induce rock failure posing risk to reservoir longevity, reservoir productivity, induced seismicity (Ellsworth 2013; Sewell et al. 2015; Sherburn et al. 2015), wellbore stability (Zoback 2010) and surface subsidence (Allis et al. 2009; Keiding et al. 2010). Understanding the conditions that may precede failure by macroscopically brittle or ductile deformation important. The ability to model these problems is limited by the lack of triaxial deformation data on rocks from geothermal systems.

To address this, we present failure criteria for three altered andesite units from the Rotokawa geothermal field. These will be used for numerical modelling of wellbore stability in the Rotokawa geothermal field during drilling, production and injection.

2. MATERIALS AND METHODS

2.1 Rotokawa Andesite

The Rotokawa Andesite (RKA, Taupo Volcanic Zone, New Zealand), hosts a high-enthalpy geothermal system. The RKA consists of a complex series of andesitic lavas and breccias, with significant hydrothermal alteration from the existing geothermal system (Siratovich et al. 2016). The primary mineralogy consists of plagioclase and pyroxene phenocrysts in a groundmass of microscopic plagioclase, pyroxene, and titanomagnetite microlites (Figure 1). Pyroxene phenocrysts are significantly altered to chlorite, quartz, calcite, and epidote (Siratovich et al. 2016). The groundmass of these materials is also strongly altered to chlorite and silica minerals. The nature of the porosity varies between the units, with open, filled, dissolved pores, and inter- and trans-granular fractures present.

We selected samples of moderately and highly altered, argillic to propylitic alteration defined in Wyering et al. (2014), andesite lava and breccia from three different wells at depths ranging from 1852 to 2314. The connected porosity varied from 0.068 to 0.178.

2.2 Experimental Methods

We sampled 20 mm diameter, 40 mm long cores from large-diameter drill core. The samples were deformed under saturated conditions at constant pore pressure, in triaxial compression at an axial strain rate of 1.0×10^{-5} s^{-1}. Differential is the axial stress minus the confining pressure. By maintaining the pore pressure constant during deformation, we could continuously monitor changes in porosity as water was ejected from the sample (porosity decrease) or sucked into the samples (porosity increase). Siratovich et al. (2016) contains a full description of the testing apparatus.

2.3 Development of failure criteria for the RKA

We used the Hoek-Brown failure criterion [1] for intact rock (Hoek and Brown 1980; Eberhardt, 2012), to develop the saturated failure criteria for the RKA.

$$s'_1 = s'_3 + UCS\left(m_i \cdot \frac{s'_3}{UCS} + 1\right)^{0.5} \qquad [1]$$

where UCS is the peak axial stress (σ'_1 = differential stress + Peff) at failure under uniaxial conditions (no confinement, σ'_3 = Peff = 0) and m_i is an empirical curve fitting parameter.

We used this failure criterion, rather than the Mohr-Coulomb failure criterion because it can be plotted in principal stress space, allowing simple comparison of induced stresses to the failure criterion.

2.4 Numerical Modelling Methods

We constructed a finite element model (Phase2, Rocscience) of a water-filled vertical well corresponding to the RKA at 2200 m depth (Figure 2). The model contains the failure criterion for the RKA containing a porosity of 0.096, horizontal *in-situ* effective stresses according to Davidson et al. (2012), and production and injection are simulated using distributed forces around the excavation boundary.

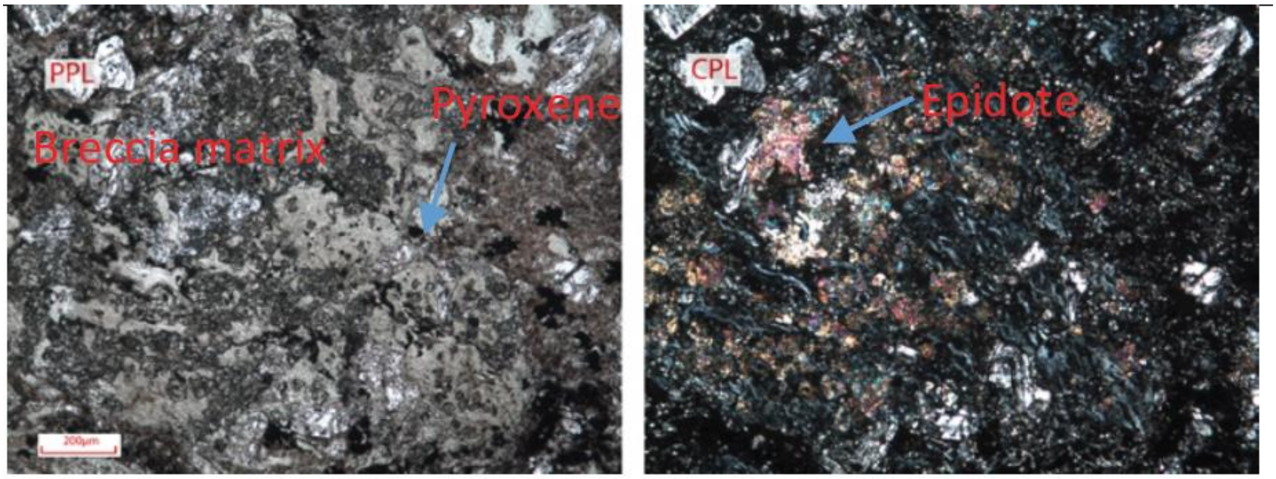

Figure 1: Highly altered andesite breccia from well RK 27 at 1852 m depth. "PPL" refers to plane polarised, and "CPL" to cross polarised light (from Jones, 2016).

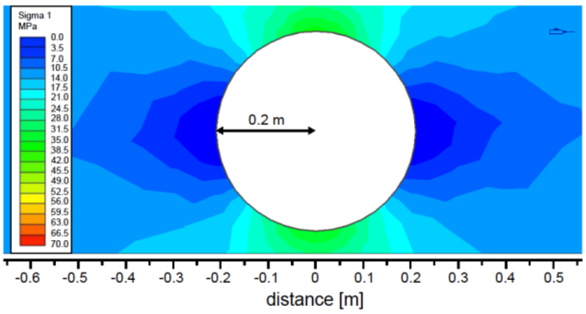

Figure 2: Finite element model of vertical well at 2200 m depth showing induced major principal stresses around the well (from Siratovich et al., 2016).

3. RESULTS

3.1 Triaxial Deformation

The results of the triaxial deformation tests on the RKA with porosity 0.096 show that strength increases, and behaviour becomes more ductile as the confinement increases (Figure 3). The results of triaxial deformation tests on the RKA at constant confinement and alteration, but varying porosity, show that strength decreases with porosity (Figure 4).

3.3 Failure Criteria for the RKA

We constructed the failure criterion constructed for the RKA with porosity 0.096 (Figure 5) and plotted them with failure criteria from Volcán de Colima (Heap et al. 2015a) and from Whakaari (Heap et al. 2015b).

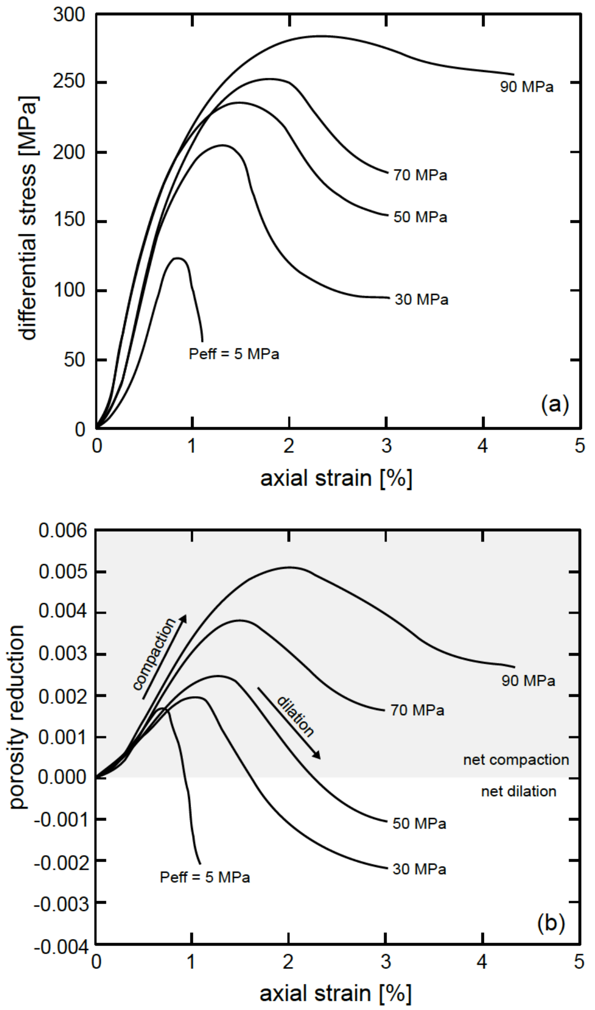

Figure 3: Triaxial test results for RKA with 0.096 porosity (from Siratovich et al., 2016).

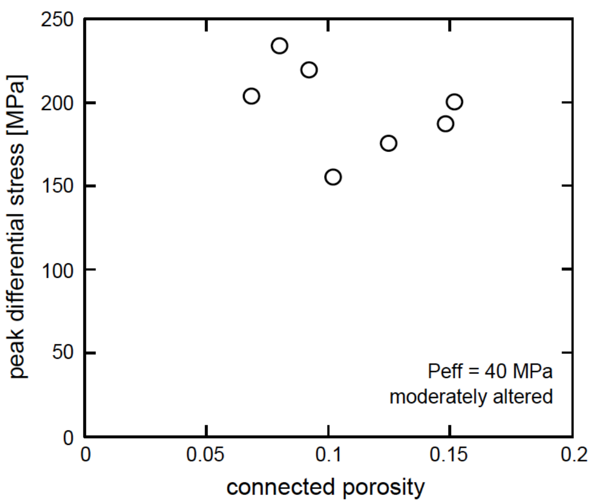

Figure 4: Relationship between connected porosity and peak differential stress (from Siratovich et al., 2016).

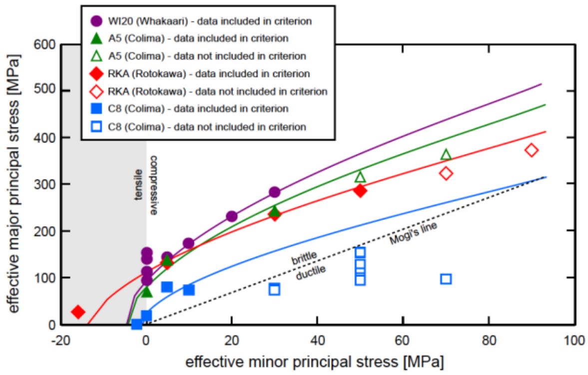

Figure 5: Failure criterion for RKA with porosity 0.096 and published values from surface volcanics (from Siratovich et al., 2016).

3.3 Wellbore and reservoir stability modelling

The stress change paths (Figure 6a) for during drilling, and subsequently for reinjection or extraction, are shown for the top of the wellbore (as viewed in the model) at a distance of 0.01 m away from the excavation boundary. Similar stresses for 0.1 m from the boundary of the wellbore are given, and follow similar stress change paths. The initial stress state is the undisturbed reservoir condition.

The reinjection and extraction induced stresses (Figure 6b) represent the perturbed reservoir stresses resulting from changes in pore pressures during reservoir utilisation. Note that the samples with a porosity of 0.151 and 0.178 were not extracted from 2200 m and therefore this stress-strength combination is indicative of possible scenarios only.

4. DISCUSSION

The brittle behaviour observed in our triaxial experiments implies that induced seismicity through initiation of new fractures in intact rock is possible in the RKA. Changes in differential stress or pore pressure around the wellbore or in the reservoir could induce failure of intact rock if the strength of the intact rock (for example the failure criteria given in Figure 6b) is exceeded. Production-induced compaction may be possible in rocks with lower strength than those tested in this study, but unlikely in the RKA.

The injection pressures used at Rotokawa are less than 1.5 MPa and are unlikely to induce a stress state that would cause failure in all but the most porous and/or most altered rocks (e.g. Figure 6b for RKA containing a porosity of 0.178) in the large scale reservoir. However, there is a possibility that local accumulations of injected fluid may elevate pore pressure significantly enough to cause stress states favourable for deformation. This has been described by Sherburn et al. (2015) and the accepted “compartmentalisation” of the RKA reservoir (see McNamara et al. 2015) may allow development of local zones that promote both dilation and compaction in the reservoir rock purely through changes in effective pressure during injection.

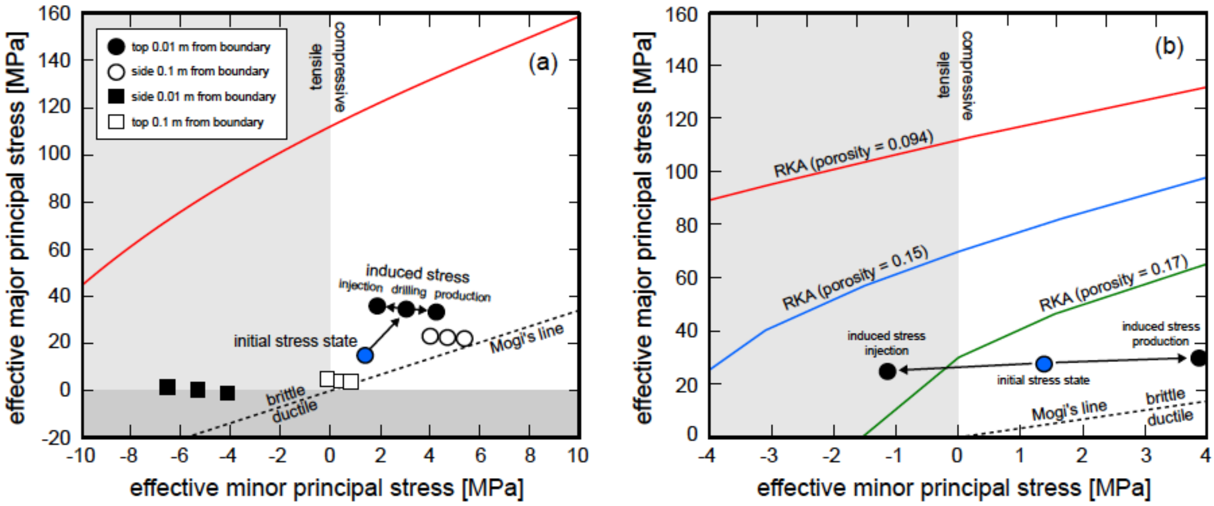

Figure 6: (a) Principal stress plot showing the modelled induced stresses in a well at 2200 m depth compared to the failure criterion for the RKA containing a porosity of 0.096; (b) Principal stress plot showing the *in-situ* stresses in a well at 2200 m depth compared to the failure criteria for the RKA samples containing a porosity of 0.096, 0.151, and 0.178 (both panels from Siratovich et al., 2016).

5. CONCLUSIONS

We have demonstrated that the RKA is brittle over reservoir pressures. We infer that brittle deformation will dominate within the reservoir under the current stress regime. Seismic activity in the reservoir is more likely to arise from thermal contraction and slip on already critically stressed faults than as a result of porewater pressure changes.

We have further shown that drilling-induced wellbore damage is unlikely. Production and injection are unlikely to induce compaction of the near-well reservoir; however, shearing and associated dilation is possible during injection in the units with high porosity and/or high alteration intensities.

This paper presents a study that is the first of its kind exploring the deformation behaviour of an altered geothermal reservoir rock under varying pressure conditions. We have shown that the failure criteria we have built are can be used to assess stress-induced behaviour at the wellbore and in the reservoir. Further study on these and similar rocks will yield further insight into the mechanisms that control geothermal reservoir behaviour.

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