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Experimental Thermal Stimulation of the Rotokawa Andesite

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ABSTRACT

Thermal cycling of rock by heating and rapid quenching in water significantly affects its physical, mechanical and elastic properties. In this study we present a novel technique where specially designed equipment simulates the cyclic thermal stimulation processes employed by the conventional geothermal industry. To enhance productivity and injectivity of geothermal wells, geothermal operators commonly inject fluids cooler than reservoirs into wells at pressures less than natural fracture gradients which can result in enhanced fluid handling capacities. In an attempt to better understand this process, the investigation of thermal stimulation at a laboratory scale has been conceived and implemented. We have designed and built an apparatus that allows the heating and quenching of representative samples by thermal stimulation in a pressure vessel capable of attaining 350°C and 24 MPa and sustaining pressure during quenching cycles. Core sourced from production wells in an active commercial geothermal field has been tested in the apparatus. Our studies have characterized specimens prior to and subsequent to thermal stimulation for density, porosity, permeability, micro-structural texture, mineralogical fabrics, acoustic velocities, dynamic and static elastic moduli. Our results indicate that our stimulation apparatus is capable of enhancing both microscopic and macroscopic permeability, increasing porosity, reducing bulk density and attenuating seismic velocities. We have enhanced porosity in our specimens by up to 1.0 (vol%) over original values, attenuated compressional wave velocities by up to 15% and enhanced permeabilities by nearly an order of magnitude over initially observed values. We utilize scanning electron microscopy to evaluate the microstructural change to samples, supplementing physical property investigations. The results imply that thermal stimulation can be successfully replicated in the laboratory and is coupled with both thermal and chemical components. The implications of this study for future laboratory and field scale stimulation testing are then considered.

1. INTRODUCTION

Thermal stimulation of geothermal wells is a technique that is used to enhance near-wellbore permeability in wells that are under-performing (Kitao et al., 1990; Flores-Armenta and Tovar-Aguado, 2008) and is a known phenomenon in wells that are used for long-term reinjection of spent reservoir fluids (Grant et al., 2013). This process can be done immediately after wells are drilled to enhance the fluid handling capabilities of the wells or can be carried out long after the wells have been utilized and may be experiencing a decline in productivity or injectivity.

Cracking can occur in the wells that can be linked to tectonic stress in the reservoir environment, coupled with thermoelastic stress that results from injection of fluids that are cooler than the reservoir formations. These fluids may be waste streams from power-plants that can range in temperature from 40-180ºC or can be from nearby fresh water sources where it is necessary to maximize the thermal gradient applied to the reservoir formations. Both injection streams are of a lower temperature than those found in the reservoir and thus a differential thermal stress is created. However, thermal cracking cannot be exclusively identified as the single clear physical mechanism that creates permeability enhancement. The thermal stresses have been postulated to create new fractures, re-open existing sealed fractures and dilate open fractures by contraction of the surrounding rock through cooling. It has been suggested that stimulation may also be achieved without thermal cracking by cleaning out debris from open fractures that have been plugged during drilling and completion operations (Axelsson and Thórhallsson, 2009), or chemically by dissolving fracture filling minerals and enhancing permeability of existing fractures (Flores et al., 2005; Pasikki et al., 2010).

The subject of thermally induced cracks in the laboratory is not a new field of research and has been proven to influence many important physical properties. Specifically applicable to geothermal development are investigations of permeability increase, strength degradation and acoustic velocity attenuation (e.g. Darot et al., 1992; David et al., 1999; Vinciguerra et al., 2005; Nara et al., 2011) . The majority of these studies have been carried out on granites and other isotropic media. Milsch et al., (2008) presented long-term, low flow rate studies of rocks similar to the geothermal system at Groß-Schönebeck, coupled with permeability measurements. However, there is a distinct lack of information on geothermal core and thermal cracking in the laboratory under fully water saturated conditions, coupled with high thermal gradients and rapid fluid flow-rates.

We have conducted experiments to constrain the processes that may result in permeability enhancement in a geothermal reservoir environment, and have carried out a series of tests on core sourced directly from an active geothermal reservoir. We have characterized important physical properties before subjecting the cores to high-temperature thermal stimulation tests using a specially designed "geothermal stimulation device" (Figure 1). The results of our investigation and implications for geothermal stimulations are then discussed.

2. EXPERIMENTAL PROCEDURES

We have utilized core sourced from the Rotokawa Andesite, the reservoir lithology of the high-temperature, high-enthalpy geothermal reservoir at the Rotokawa geothermal field, located in the Taupo Volcanic Zone, North Island, New Zealand. Five samples of Rotokawa Andesite were cut into cores 20 mm diameter by 40 mm length, and characterized for porosity, density, permeability, and acoustic wave velocities.

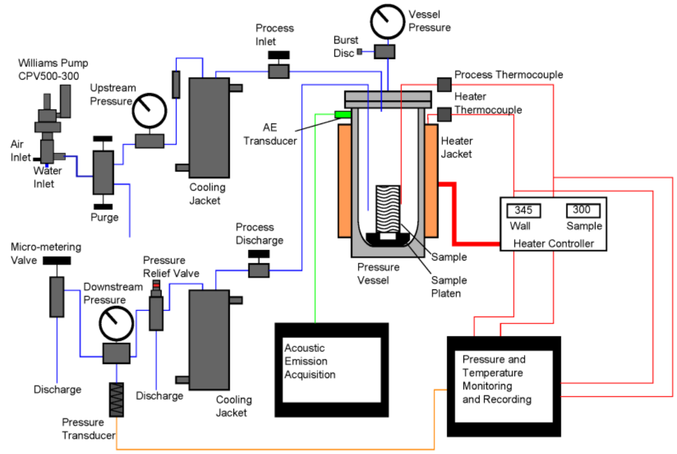

Figure 1: Thermal stimulation apparatus schematic used in treatment of Rotokawa Andesite samples.

Porosity and bulk density of the samples were determined using the triple-weight water saturation method (Ulusay and Hudson, 2007). Permeability was determined at the Laboratoire de Déformation des Roches (LDR, Université de Strasbourg) using a gas permeameter with argon gas as the pore-pressure media and distilled water as the confining media (see Heap et al., 2014 for further description). All samples needed Klinkenberg slip correction applied to determine true permeability (Klinkenberg, 1941). Ultrasonic wave velocities were measured at the University of Canterbury using a GCTS CATLS ULT-100 (Geotechnical Consulting and Testing Systems Computer Aided Ultrasonic Velocity Testing System) with axial P- and S-wave piezoelectric transducer crystals with a resonance frequency of 900 kHz. The acoustic measurements were conducted under a force of 1.5 kN provided by a Tecnotest servo-controlled loading frame to ensure consistent contact of the transducers and repeatability of the axial load applied to the samples. Ultrasonic velocities and measured densities were utilized to calculate the dynamic Young's modulus (E_d) and Poisson's ratio (v_d) (Guéguen and Palciauskas, 1994).

The samples were then subjected to thermal stressing under confined, high temperature, water saturated conditions. They were heated at 2ºC/min to a target temperature of 325ºC, and held for two hours. The system was quenched using 20ºC water at a flow rate of 145 ml/min to a final temperature of 20ºC while maintaining a system pressure of 20 MPa. The peak quenching rate is >27ºC/min in the initial portion of the cooling cycle and averages 10.9ºC/min from 325ºC to 100ºC and further declines to 2ºC/min from 100ºC to 20ºC as evidenced in Figure 2a. Acoustic emissions were monitored during the sample cycle using the Mistras AE (acoustic emission) acquisition system using a Physical Acoustics D9215 high temperature sensor with frequency range set to 100-500 kHz (Figure 2b). The thermal stimulation system schematic, pressure, temperature and acoustic output during a thermal cycle of Rotokawa Andesite are presented in Figure 2, detailing an example of a thermal stimulation cycle in the device.

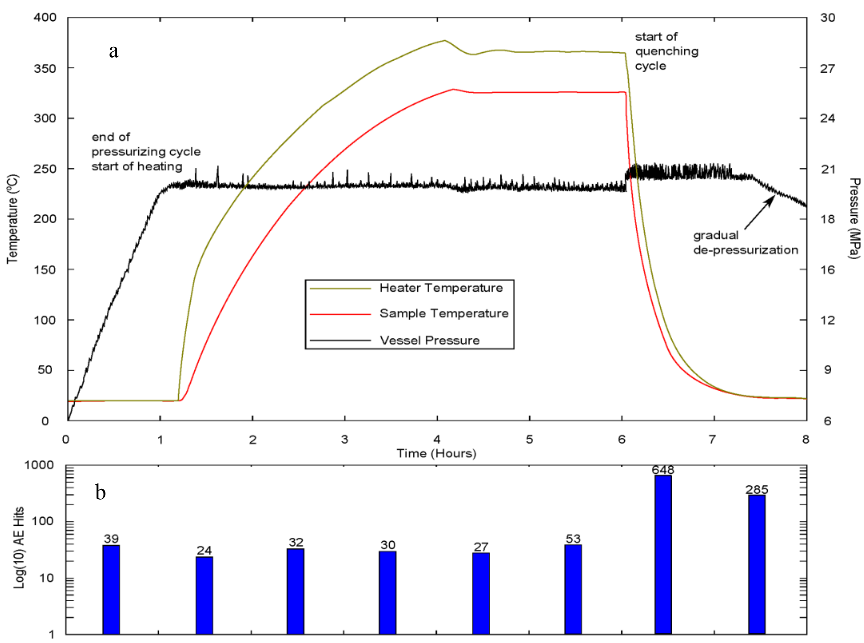

Figure 2: (a) Pressure, temperature profiles during experimental thermal stimulation treatment of Rotokawa Andesite sample RK27-3.7a. (b) Total acoustic emission output observed during thermal stimulation testing.

RESULTS

Figure 3 details the key physical parameters that were measured to gain an understanding of how thermal quenching after heating may influence the properties of the Rotokawa Andesites. Porosity shows an average increase of 0.7 (vol%) with a range of 0.5-1.0 (vol%) change in porosity across the dataset (Figure 3a). This is coupled with a marked increase in permeability for all samples, where the mean value of permeability has increased from $2.9*10^{-17}$ m^2 to $2.3*10^{-16}$ m^2 across all samples, such that the stimulated values are an average of 7.8 times more permeable. This is neither a trivial nor insignificant shift and shows that we have achieved an increase in permeability for the Rotokawa Andesite following our stimulation methodology. Accordingly, we see a marked decrease in our acoustic wave velocities with average compressional wave attenuation of 540 m/s and shear wave velocities showing average attenuation of 96 m/s. The reduction in these velocities show that we have created cracking in the samples as the acoustic properties are very sensitive to the presence of cracks in the material (Stanchits et al., 2006). Figure 3b shows the graphical representation of the acoustic attenuation where both Vp and Vs are significantly reduced following thermal treatment which is a direct indication of an increase in microfracture densities (Anderson et al., 1976; Stanchits et al., 2003). Coupled with measurements of bulk density and attenuated acoustic velocities we subsequently show a significant decrease in the dynamic Young's modulus and Poisson's ratio (Figure 3c) after thermal stimulation testing.

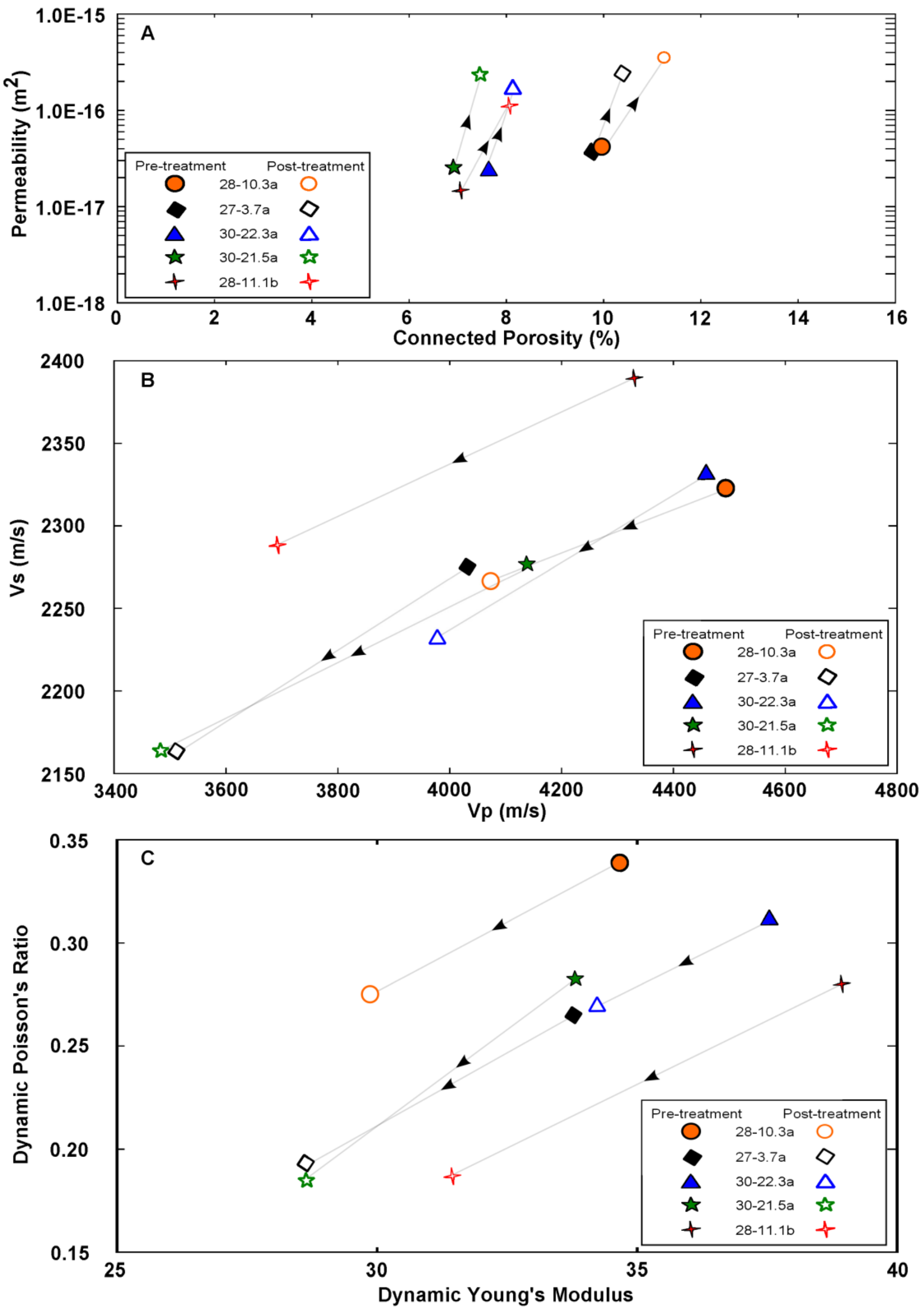

Figure 3: Pre-treatment and post-treatment comparisons of physical properties of Rotokawa Andesite (a) Porosity and permeability. (b) Compressional wave velocities (Vp) and shear wave velocities (Vs). (c) Dynamic Young's modulus and Poisson's ratio

To support our macroscopic property investigations indicating that fracturing has occurred in the samples, we utilized backscattered scanning electron microscopy on the sample surfaces. An examination of pre-test (Figure 4a and 4c) and post-test (Figure 4b and 4d) scans shows that the microstructure of the samples has changed as a result of the thermal stimulation procedure. The stimulation process appears to force a dissolution of the sample structure with a preference for the matrix while phenocrysts retain some original fabric but are also largely altered. This is further supported by Figure 5 where the sample was in contact with the platen at the base of the sample chamber and no alteration is observed where water has not been in contact.

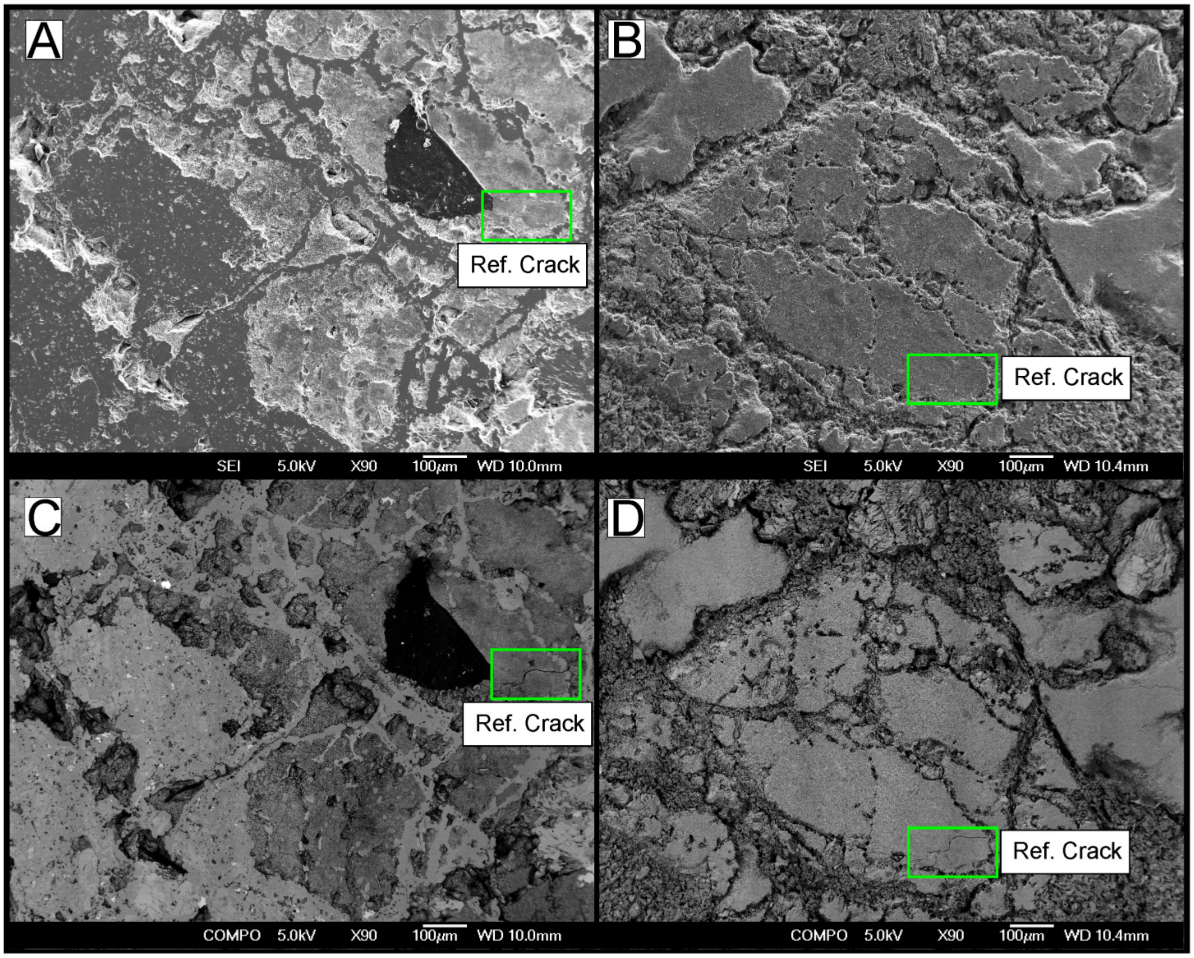

Figure 4: Scanning Electron Microscope images of Rotokawa Andesites with reference crack highlighted to orient sample in microscope field of view (A) Pre-treatment secondary analysis image showing likely plagioclase phenocrysts and ferromagnesian ground-mass. (B) Post-treatment secondary analysis image showing greater relief and preferential nature of chemical etching. (C) Backscattered pre-stressing image showing groundmass and hydrothermally altered phenocrysts. (D) Backscattered post-stressing image showing pervasively etched phenocrysts, groundmass and significantly higher fracture density in phenocrysts with preferential etching.

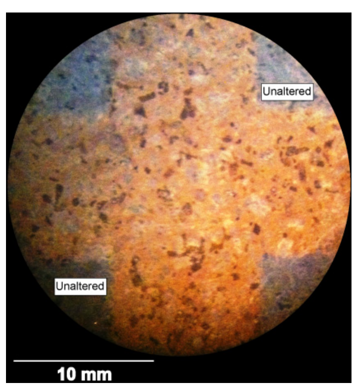

Figure 5: Post-Treatment Rotokawa Andesite showing altered and unaltered portions of core where the sample sat on the platen in the pressure vessel.

DISCUSSION

Thermal stressing under laboratory conditions has been carried out on rocks of varying composition at various heating and cooling rates (e.g. Yong and Wang, 1980, Chaki et al., 2008; Keshavarz et al., 2010). In almost all cases where thermal treatments are applied, permeability is increased by the treatment (see David et al., 1999 and Nara et al., 2011 for further discussion). However, many of these studies are carried out on rocks that have been erupted and slowly cooled and been used for quarrying materials and building materials for some years (e.g. Westerly Granite, Frederick Diabase; see Yong and Wang, 1980; Fredrich and Wong, 1986). No studies have been carried out on geothermal core with the explicit aim to increase permeability under controlled temperature conditions and fully water saturated environments using high cooling rates and high flow rates. We have demonstrated the ability to enhance permeability through our experiments and this is seen in Figures 2 and 3.

We have stressed these rocks to temperatures that they would have been subject to prior to exhumation by drilling (Rae, 2007), and do not anticipate that additional damage would result from thermal stressing whatever the heating rate (as observed by Yong and Wang, 1980). It is however possible that during our rapid cooling, we are placing instantaneous stress by thermal gradients on already existing cracks and propagating those cracks. This is evidenced by acoustic emissions that we have observed during the thermal cycling. As such, we have to consider that significant thermal stress is being imparted on rocks that have a complicated thermal and chemical history.

A close inspection of the SEM images shows that there is significant surface chemical interaction occurring in the samples. There is apparent preferential dissolution of plagioclase and significant dissolution of several other mineral species that are present in the material. This dissolution is extensive and we consider this to indicate that there must be a disequilibrium of the fluids used in our stimulation with those that are the resident in the reservoir, and that this reaction is both thermally and chemically complex. We must also consider that the depth at which the alteration occurs is only a small fraction of the total volume of the sample. It is possible that the thermo-chemical reactions we see at the surface are able to penetrate into cracks that pervade the rock masses, but that the entire sample is not subject to this alteration as seen in Figure 4.

The implications of the thermal and chemical components of this study are significant as in real-world thermal stimulations, when large volumes of water pumped down wellbores sourced from nearby water sources or cooling tower basins, these are largely enriched in oxygen compared to those fluids in the reservoir. We must therefore conclude that there is a significant oxidation of the reservoir rocks and this may serve to work as a chemical 'wedge' of sorts for propagation of fractures. It is widely accepted that thermal cracking is isotropic in nature. However, this does not account for significant chemical changes that may initiate mechanical cracking as a result of weaknesses created by chemical erosion.

Further work should replicate reservoir brine chemistries at ambient temperatures to see if the same chemical erosion occurs. It may be possible that the oxidation and erosion we observe is simply a forced washing of our samples, but at this stage it seems thermal stimulation may be enhanced down-hole at the wellbore face and within reservoir rocks by the introduction of variable fluid chemistries.

Our study has shown that permeability is enhanced by our testing method which is the fundamental goal of any thermal stimulation procedure and has implications for larger scale borehole stimulations. We have shown that permeability is greatly enhanced by cold water stimulation in the laboratory and this reinforces the need to further study how to optimize this procedure and benefit geothermal projects worldwide.

In conclusion, our study is the first of its kind to directly simulate thermal stimulation on cores sourced directly from a geothermal reservoir, with the explicit goal of permeability enhancement through rapid thermal quenching under high flow rates. Our geothermal stimulation device realistically replicates the temperatures and pressures that may be encountered in a down-hole environment. We find that cold water shocking of the core results in an increase of intrinsic permeability as a result of additional thermal cracking, but chemical disequilibrium must be considered when conducting further experiments.

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