THE GEOTHERMAL STIMULATOR: A HIGH-TEMPERATURE, HIGH-PRESSURE DEVICE FOR INDUCING THERMAL FRACTURE IN ROCKS

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ABSTRACT

Thermal cycling of rock by heating and rapid quenching in water significantly affects its physical, mechanical and elastic properties. Understanding the processes that lead to these changes is relevant to nuclear waste repositories, tunnel excavations and geothermal energy production. In this study we present a novel technique where specially designed equipment simulates the wet, cyclic thermal stimulation processes employed by the conventional geothermal industry. To enhance productivity and injectivity of geothermal wells, operators commonly inject fluids cooler than the reservoir into wells at pressures less than the natural fracture gradient. By thermally stimulating core samples in a pressure vessel capable of attaining 350°C and 24 MPa, we attempt to replicate conditions encountered at depth in geothermal reservoirs during stimulation procedures. We establish baseline physical and acoustic properties, (compressional (Vp) and shear (Vs) acoustic wave velocities), porosity and density, and dynamic elastic modulii. We compare these baseline properties to those of specimens subjected to four different heating and cooling cycles: (1) heated to 300°C and slowly cooled without quenching, (2) heated to 300°C and quenched, (3) heated to 300°C, quenched and repeated, and (4) heated to 300°C quenched and repeated for three cycles. We observed a decrease in acoustic wave velocities and elastic modulii in the thermally treated samples when compared to the baseline samples. The study has shown that microscopic fractures form as rocks are heated and rapidly quenched by water under simulated geothermal reservoir conditions, and those fractures attenuate acoustic velocities and significantly affect the dynamic and static stiffness modulii of the samples.

1. INTRODUCTION

The mechanical degradation and change of fluid transport capabilities of rocks as a result of thermal stressing is a very important research question that spans the practical fields of geothermal energy production, nuclear waste repository security, volcanic stability and building materials engineering. Geothermal wells can be enhanced by induced thermal gradients in the reservoir rocks (Kitao et al.,1990, Axelsson and Thorhallsson, 2009, Flores et al., 2008, Siega et al., 2009). In addition, alteration of rocks by heating and cooling of volcanic edifices can significantly change their host rocks and also change seismic properties of those rocks, potentially contributing to volcanic weakening (Vinciguerra et al., 2005, Heap et al., 2009). Here we present the initial results of testing of a geothermal stimulation device designed to replicate thermal stimulation procedures carried out at geothermal fields to enhance productivity and injectivity of wells (Axelsson et al., 2006).

While it has long been understood that thermal stimulation is an excellent enhancement technique, the process is poorly understood (Grant and Bixley, 2011) and further investigation is needed (Siratovich et. al, 2011).

Thermal and physical damage of rocks in the laboratory has been extensively studied in an effort to understand the evolution of physical and mechanical properties. Heating damage to rocks has been shown to significantly alter porosity, permeability, uniaxial compressive strength, acoustic velocities and acoustic emissions during failure testing. Homande-Etienne and Troalen (1984) published one of the ground-breaking papers on the role of thermal cracking on texture, porosity and permeability of granites and limestones. This work indicated that the majority of damage within the samples occurred as a result of expansion of inter-crystalline boundaries and this as a result increases the effective (open) porosity of the rocks. Later, Geraud et al., 1994, David et al., 1999, and Yavuz et al., 2010 indicated that dispersed cracking of mineral grains and intergranular expansion during heating is the dominant source of increased porosity during heating of rock specimens. These studies found clear correlations between the induced maximum temperature of the sample and physical properties such as porosity and acoustic wave velocity. Complementary to these studies, it has been well documented that increased porosity and permeability in conjunction with decreased acoustic velocities result from thermal damage to rock samples (Darot et al., 1992, Jones et al., 1997, Vinciguerra et al., 2005). Several other authors have also observed physical and mechanical degradation of rocks by heat-induced damage (Keshavarz et al., 2010, Balme et al., 2004, Patel et al., 2012)

In this study, we present a novel device for thermally shocking rock samples under pressures equivalent to hydrostatic within a geothermal system (Grant and Bixley 2011). We also present the initial results as proof of concept for our apparatus as we have significantly changed physical, mechanical and acoustic properties of our source rocks. We characterize porosity, dynamic and static elastic modulii as well as compressional (P-Wave) and shear (S-wave) velocity profiling for in-tact rocks.

2. MATERIALS USED

2.1 Allandale Rhyolite

The Material used for this study was that of the Allandale Rhyolite (AR), pre-Lyttelton Volcanic Complex (~13-12 Ma) located in Gebbies Pass, Banks Peninsula, Canterbury, New Zealand (Hampton and Cole, 2009). These specimens are microspherulitic and are composed predominantly of quartz and feldspar (Speight, 1922). The AR was chosen for this study for several reasons: its close proximity to facilities at University of Canterbury, ease of sample preparation, and similarity to rhyolites found within the Taupo Volcanic Zone that serve as reservoir rocks for several geothermal systems (Wood, 1995, Rosenberg and Hunt 1997, Bignall et al., 2010). We characterized the physical, mechanical and elastic properties of the Allandale rhyolites used in this study to determine how and if any changes to these properties occurred as a result of thermal stressing. In order to do this it was necessary to gain a fundamental understanding of the ranges of porosity, density, acoustic wave velocities and mechanical properties.

2.2 Sample Preparation and Physical Property Measurements

Cylindrical samples were cored from a single specimen of the Gebbies Pass Rhyolite with a nominal diameter of 20.6 mm and cut and ground (within 0.01mm) to a nominal length of 50.7mm, this yielded samples with length to diameter ratios slightly greater than 2.5:1 according with methods established by ISRM suggested methods (Ulasay and Hudson, 2006). Additionally, the 20.6mm is consistent for the lithology study to allow a 10:1 maximum grain size to diameter of the specimen as the largest phenocrysts observed are in the sub 2mm range. Density and porosity of the specimens were determined using the ISRM dual-weight method (Ulasay and Hudson, 2006).

Dynamic elastic modulii and compressional wave (Vp) and shear wave (Vs) velocities were determined using a constant load on each sample of 10 MPa via a Tecnotest servo-controlled 3000 kN loading frame. The load of 10 MPa was used to ensure a consistent waveform across the specimens and ensure that the same load was applied for every testing cycle. This was determined to be below crack-closure stress and ensured a quality interpretation of the first arrival time of acoustic pulses. The velocities were determined using the GCTS testing apparatus with axial P and S wave piezoelectric crystals. Pulse frequency was 20 MHz. The dynamic Poisson's ratio and Young's Modulii are calculated based on the following equations using the Vp and Vs velocities.

Equation 1: Dynamic Poisson's Ratio Calculation

$$v_d = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)}$$

Equation 2: Dynamic Young's Modulus Calculation

$$E_d = \frac{(1 - 2v_d)(1 + v_d)}{(1 - v_d)} \rho V_P^2$$

Where Vp is compressional wave velocity in m/s, Vs is shear wave velocity in m/s v_d is the dynamic Poisson's ratio and ρ is density in kg/m^3, averaged results for the as-cut dataset are presented in Table 2.1.

Table 2.1 Physical Properties of Allandale Rhyolite

	Porosity (%)	Density (g/cm^3)	Vp (m/s)	Vs (m/s)	Poisson's Ratio	Young's Modulus (GPa)
Average	**8.64**	**2.362**	**3007**	**1678**	**0.276**	**17.50**
Standard Deviation	0.65	0.016	188	95	0.012	2.02

3. THE GEOTHERMAL STIMULATOR SYSTEM PROPERTIES

3.1 Design Parameters

A simple to use, easy to operate high-temperature moderate pressure stimulation system was needed to carry out the heating and cooling of rocks under pressures representative of those found in geothermal systems. To achieve these goals, a system capable of maintaining internal temperatures >350°C for several hours at a time and pressures above 25 MPa was developed. The confining media of the vessel was to be distilled water with the ability to convert the system to use waters sourced from geothermal steam-fields, power plant condensates and the like, so a simple feed to the system was crucial to its success. Additionally, the system had to be able to sustain a 'quenching' cycle where system pressure was maintained while cooling of specimens was forced by cooling water flow through the sample chamber. The system also had to be relatively user-friendly, low maintenance and ensure a high safety factor due to the temperatures and pressures involved being well over ambient laboratory conditions.

3.2 Apparatus Overview

The key elements of the stimulator system are a bolted closure reactor vessel, ceramic jacket heater and pressurization system, each serving a distinct role. The specimen is placed inside the pressure vessel on a hardened stainless steel (316 grade) platen that is notched to allow fluid to fully encircle the sample on the vessel bottom. The sample chamber is then bolted shut with the specimen located on the platen. The system is flooded with water and all head-space and air in the system removed from the vessel and tubing. A Williams HRV-500 pump is then fed with an air supply of 5-10 bar(g) that pumps distilled water through the system at a variable rate of 0.1 to 8.71 L/H using a timer control. The heater provides thermal input to the vessel chamber and heats both the specimen and the surrounding water.

3.3 Data Collection System

The monitoring of the stimulation process is by visual gauges that provide the user with information on temperatures and pressures inside the system during operation. Data is collected during testing via two thermocouple feeds to a LabView dataDAQ that monitors temperature at the vessel wall and a thermocouple that monitors the sample temperature. A 100 MPa pressure transducer is also fed to the LabView software that monitors pressure within 0.001 MPa. Acoustic emissions (AE) are monitored via the Mistras AE software and USB nodes. The AE node is connected to the pressure vessel via a high-temperature geophone with a frequency range of 20 kHz to 1 MHz. The AE acquisition is set up to record any emissions above 55 dB as background laboratory noise saturates the acquisition system below this threshold.

3.4 The System in Action: Pressure Profiles, Temperature Profiles and Comparison of Heating Cycles

The operation of the geothermal stimulator is relatively simple, easy to operate and requires little maintenance over several cycles of heating and cooling. The operator places a sample on a steel platen in the bottom of the pressure vessel (Figure 1) and bolts the vessel shut.

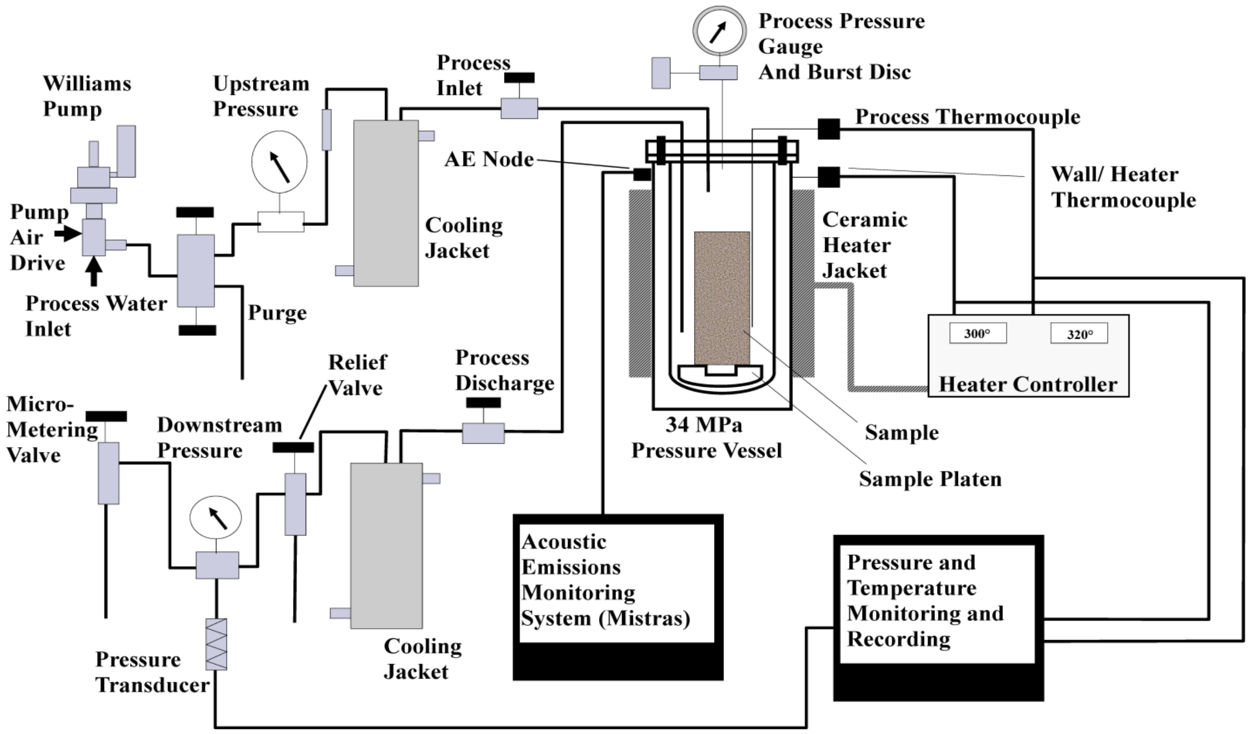

Figure 1: Geothermal Stimulator System Schematic. The system consists of three distinct components, pressurization and maintenance, heating element and controllers and pressure, temperature and acoustic emission monitoring.

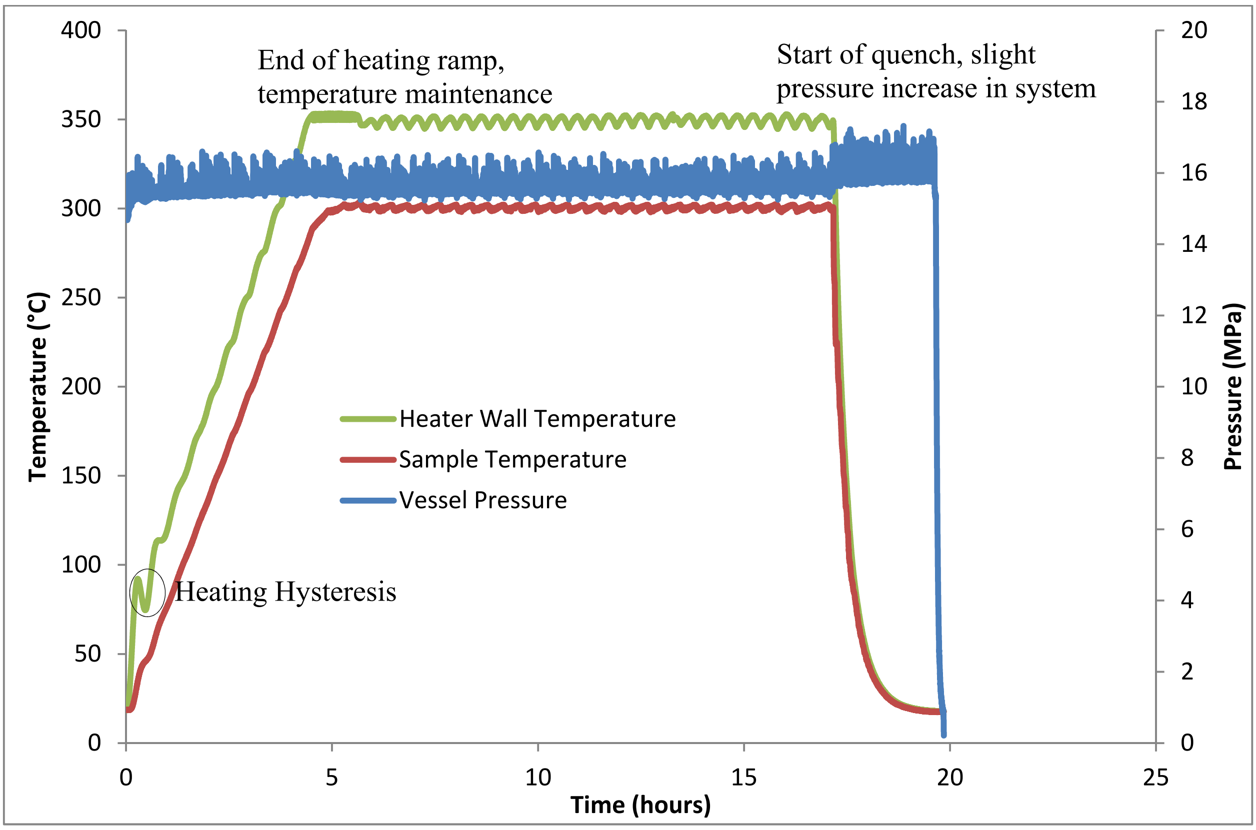

Figure 2: Temperature and pressure profiles for a quenching cycle of Allendale Rhyolite.

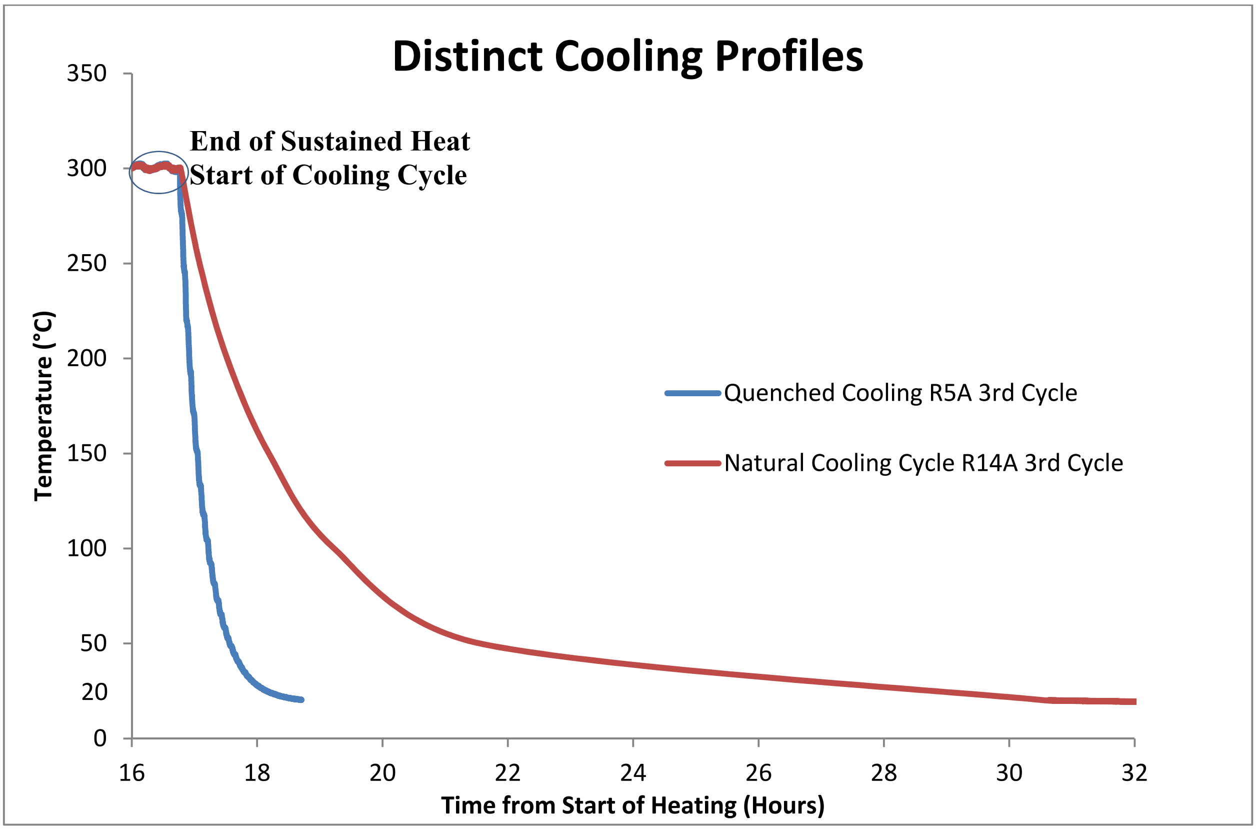

Figure 3: Detail of cooling profiles for the quenching cycle and cooling cycle without quenching water.

The operator then fills the system via the Williams pump and purges all air from the system. The heating controller is then switched on and heats at 1°C/min (variable rates allowable of 0.1 to 10°C/min) until the desired temperature is reached. The Williams pump operates on a 2 minute cycle to ensure the system is maintained at the desired pressure range and purges when over-pressured via the relief valve (Figure 1). Once the cycle ends, the user switches the Williams pump to full capacity to pump quenching water into the system (Figure 2) or the heater is switched off and the system is allowed to cool to ambient conditions with no quenching water (Figure 3).

4. RESULTS

Eight samples of Allendale Rhyolite were subjected to thermal treatment as described in section 3. Three specimens were subjected to one cycle of heating and rapid quenching (R4A, R9B, R10B), three samples to two cycles of heating and quenching (R2A, R12B, R13A) and two samples to three cycles of heating and rapid quenching (R1B and R5B).

4.1 Chemical and physical changes

After the specimens were put through the temperature cycling they were removed from the pressure vessel and observed for any qualitative property changes. We were surprised to find that the samples showed surface alteration from a dull gray colored surface to a rich brown surface and also observed noticeable softening of the outside of the specimen. This was determined to be illite clays by thin section analysis. These clays represented a slight mass loss of the sample and volumetric loss of the specimen. After re-measuring the sample geometry and re-evaluating porosity and density for the new geometries, we found that the specimen porosity increased and density decreased (Figure 4).

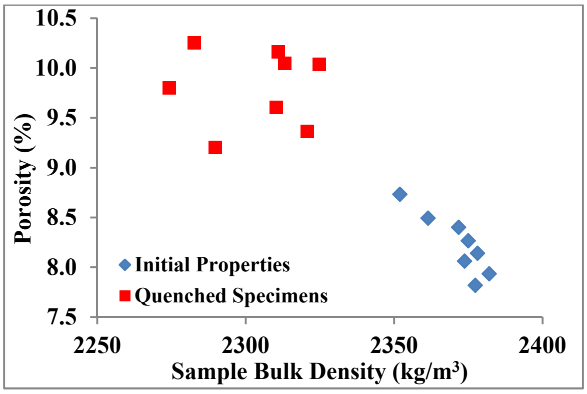

Figure 4: Bulk density and porosity for specimens that underwent rapid thermal treatment.

4.2 Changes in acoustic properties

As presented in Section 2.2, we evaluated the dynamic elastic properties and acoustic velocities of our samples before any thermal stressing experiment. After thermal stressing, we re-evaluated these properties to observe trends and changes in their evolution. Interestingly, we observe a decrease in both compressional (Vp) and shear (Vs) wave velocities in all samples subjected to thermal treatment. However, we note that the decrease of Vp is much more significant in the samples than Vs (Figure 5). This was also noted by Keshavarz et al. (2010).

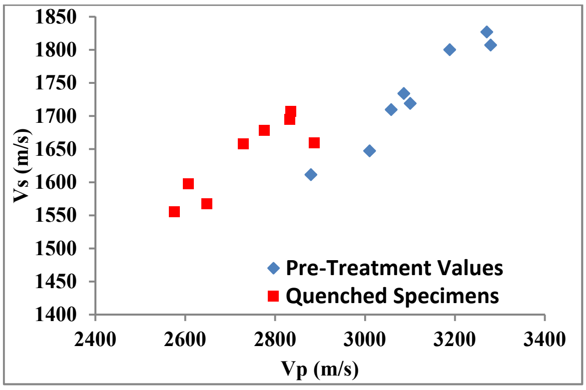

Figure 5: Comparison of sample original state prior to thermal treatment and the post treatment. We observe a decrease in both Vp and Vs for all specimens subjected to thermal treatment.

5. DISCUSSION

5.1 Porosity and density

In each specimen subjected to thermal treatment the sample porosity increased and density decreased; we infer this to be the product of two mechanisms: alteration of matrix minerals to illite clays at this temperature and pressure regime and microcracking of the specimen during both heating and cooling cycles. We observe an increase in porosity and attribute this to be the result of the formation of microcracking that was observed via AE monitoring during thermal treatment. AE monitoring is a well known and accepted tool to infer microcracking during thermal treatments (Heap et al., 2013) These phenomena have also been observed by several authors in their studies on the thermal effects of porosity and other physical properties (Vinciguerra et al., 2005, Chaki et al., 2008, Lokajíček et al., 2012).

5.2 Effects of thermal treatment on acoustic wave velocities and dynamic modul ii

Changes in acoustic wave velocities have been investigated by several authors and in almost all cases, the velocities are attenuated after thermal treatment. This has been attributed to the development of microcracks in the samples that attenuate these waves. Keshavarz (2010) showed that Vp decreases significantly more than Vs after thermal stressing, as we have also observed. We infer that this is a result of the development of thermal cracks in specimens that were quenched due to the effect of large thermal gradients induced both at the surface and within the specimen.

5.3 Implications for thermal stimulation

The stimulation device has in effect replicated two phenomena that have been described as the physical manifestations of thermal stimulation in geothermal wells. We have observed microcracking (formation of new cracks) and matrix destruction (mass loss and clay alteration) that Axelsson et al. (2006) described to be two of the three physical processes that enhance geothermal wells (the third being re-opening of new cracks). Additionally, by utilizing open porosity, AE monitoring and acoustic profiling, we can infer that we have also increased the intrinsic permeability of the specimens (Fortin et al., 2011).

6. CONCLUSION AND FURTHER WORK

In an effort to replicate the phenomenon of thermal stimulation in the laboratory, we developed and tested a device that can replicate geothermal conditions at depth in a simple, easy to use manner. The initial testing of the device has yielded very promising results as we have increased sample porosity and reduced acoustic velocities, the latter of which can serve to infer increased crack permeability (Fortin et al., 2011). We have also attempted to replicate the thermal stimulation methodology described by Axelsson and Thórhallsson (2009) with our results indicating both mass loss (matrix destruction) and opening of new cracks (thermal microcracks).

Further work with the geothermal stimulator is to characterize sample permeability evolution in rocks sourced from core from geothermal fields in New Zealand. In addition to permeability observations we will also subject samples to mechanical investigations using both uniaxial compressive strength and tri-axial strength testing at ambient conditions and elevated temperatures.

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