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Thermoelastic properties of the Rotokawa Andesite: A geothermal reservoir constraint

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ABSTRACT

Knowledge of the thermal properties of geothermal reservoir rocks is essential to constraining important engineering concerns such as wellbore stability, reservoir forecasting and stimulation procedures. The thermo-mechanical evolution of geological material is also important to assess when considering natural processes such as magmatic dyke propagation, contact metamorphism and magma/lava emplacement and cooling effects. To better constrain these properties in the geothermal reservoir, thermal measurements were carried out on core samples from production wells drilled in the Rotokawa Andesite geothermal reservoir, located in the Taupo Volcanic Zone, New Zealand. Linear thermal expansion testing, thermogravimetric analysis, and differential scanning calorimetry were used, employing experimental heating rates of 2, 5 and 20 °C/min. Thermal property analyses can elucidate whether thermal expansion values measured under varied heating (and cooling) rates are rate dependent and if thermo-chemical reactions influence the resultant expansivity. Measured thermal expansion coefficients of the Rotokawa Andesite are shown not to be heating rate dependent. We have also found that significant thermochemical reactions occur during heating above 500 °C resulting in non-reversible changes to the thermomechanical properties. The combined thermogravimetric, calorimetric and thermomechanical analysis allows insight to the reactions occurring and how the thermomechanical properties are affected at high temperature. We incorporated results of tensile strength testing on the Rotokawa Andesite to apply our thermal property measurements to a one-dimensional thermal stress model. The developed model provides a failure criterion for the Rotokawa Andesite under thermal stress. The importance of this study is to further understand the critical heating and cooling rates at which thermal stress may cause cracking within the Rotokawa reservoir. Thermal cracking in the reservoir can be beneficial in reservoir stimulation procedures, but also poses potential risk to wellbore stability, so constraining the conditions at which this can occur can be beneficial to resource utilization.

1. Introduction

The behavior and influence of a thermal gradient on a geothermal resource can have a substantial impact on the heat flow, stress state, permeability and commercial potential of a geothermal reservoir. Induced or natural thermal gradients can cause thermal cracking in rock (David et al., 1999) which leads to the degradation of strength (Heap et al., 2013b) and an increase in permeability (Faoro et al., 2013). Detailed studies on the conditions that constrain the onset of thermal cracking in a geothermal reservoir are essential for the optimal utilization of the resource, wellbore stability considerations, reservoir forecasting, and stimulation procedures (e.g. Zoback et al., 2003; Ghassemi and Zhang, 2004; Grant and Bixley, 2011). Thermal cracking is also a significant process with regard to a number of geological phenomena, namely: magmatic dyke emplacement, contact metamorphism, and cooling of magma and lava bodies. To further the understanding of thermo-mechanical behavior in a geothermal reservoir, it is necessary to quantify the thermal properties of the reservoir rocks. The Rotokawa Andesite is one such geothermal reservoir rock that hosts a high-temperature, commercially utilized geothermal resource located in the central Taupo Volcanic Zone (TVZ), North Island, New Zealand (Powell, 2011). The Rotokawa Andesite is the main geothermal reservoir rock at the Rotokawa geothermal field and served as the source material for this study.

The optimization of a high-enthalpy geothermal energy project is highly dependent on the natural permeability of the system (Grant and Bixley, 2011). However, the perturbation of the natural state of the reservoir by drilling and extraction of heat and fluids changes the

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dynamics of the reservoir with respect to pressure and temperature (Ghassemi and Zhang, 2004). With change in temperature, the host rocks of the reservoir are subject to thermal gradients which can subsequently cause thermal cracking, enhancing formation permeability. Such thermal gradients can be induced by drilling fluids interacting with hot reservoir rocks (Brudy and Zoback, 1999), subsurface injection of spent power-plant fluids (Grant and Bixley, 2011), and targeted cold-water injection (Ghassemi and Zhang, 2004). Thermal cracks may lead to the increase of permeability of the well over both short and long time scales (Axelsson and Thórhallsson, 2009; Grant et al., 2013). New fractures can form when cooling fluids are injected to the reservoir rock to quench it, forcing the rock to contract and fracture in tension (Brudy and Zoback, 1999; Tarasovs and Ghassemi, 2012). The targeted injection of cold fluids commonly employed in the geothermal industry has been well documented as re-opening and dilation of already existing fractures and inducing the formation of new fractures (Kitao et al., 1990; Flores-Armenta and Tovar-Aguado, 2008; Axelsson and Thórhallsson, 2009; Grant and Bixley, 2011).

There is a direct correlation between the development of thermal cracks in rocks and the extent of heating and cooling experienced by a rock (Simmons and Cooper, 1978; Finnie et al., 1979; Homand-Etienne and Troalen, 1984; David et al., 1999). These thermal cracks can attenuate acoustic velocities (Vinciguerra et al., 2005; Fortin et al., 2011; Heap et al., 2013a), increase porosity (Bauer and Handin, 1983; David et al., 1999; Chaki et al., 2008), increase permeability as a result of microcracking (Heard and Page, 1982; Darot et al., 1992; Fortin et al., 2011; Nara et al., 2011; Faoro et al., 2013), degrade strength (Balme et al., 2004; Keshavarz et al., 2010; Heap et al., 2013b; Patel et al., 2013), and have a significant influence on thermal expansion coefficients (Cooper and Simmons, 1977; Lo and Wai, 1982; Lin, 2002).

Thermal cracking and decomposition in rock has been attributed to several processes: the mismatched thermal expansion of minerals, temperature gradients induced as a function of heating rate, anisotropic thermal diffusivity of minerals, the bursting of fluid inclusions, mineral decomposition and devolatilization (e.g. Cooper and Simmons, 1977; Wong and Brace, 1979; Lo and Wai, 1982; Keshavarz et al., 2010; Heap et al., 2012). Lin (2002) identified that the decrepitation of fluid inclusions from quartz crystals generated microcracks in samples of Inanda Granite. This work complemented the earlier conclusions presented by Hall and Bodnar (1989) that correlated acoustic emissions (AE) to cracks induced by the decrepitation of fluid inclusions from Westerly Granite.

Richter and Simmons (1974) studied igneous rocks and concluded that thermal expansion can be predicted at low heating rates by the mineral components of the rocks and that above 2 °C/min thermal cracks form in specimens that affect the whole rock thermal expansion coefficient. Additionally, they showed that microcrack porosity has an inverse effect on thermal expansion coefficients. In a subsequent study, Cooper and Simmons (1977) showed that with increasing temperature the severity of thermal cracking increases. They also showed that the presence of cracks can provide void space into which the rock-forming minerals can expand, accommodating their differential expansion. It must be noted that there is no general agreement that cracking in rock increases or decreases thermal expansion. Cooper and Simmons (1977) show that cracks in granites yield a higher measured apparent thermal expansion than what the constituent minerals should provide. This is corroborated by the results of Lin (2002) where cracks yielded a higher magnitude of expansion in the total sample, providing a higher thermal expansion coefficient than that of an un-cracked rock. However, Cooper and Simmons (1977) also show that microcracks provide pore space that accommodates expansion of minerals, minimizing effects from differing thermal expansivity. From this, they urge that expansion values obtained that are higher than expected (as in the case of their granites) may not represent those in the natural environment as confinement may restrict the growth of cracks as a result of natural boundary conditions.

Cooper and Simmons (1977) defined the volumetric thermal expansion coefficient as:

$$\alpha_v = \partial\varepsilon_v/\partial T \tag{1}$$

where α_v is the coefficient of volumetric thermal expansion, $\partial\varepsilon_v$ is change in strain, and ∂T is change in temperature. In order to apply Eq. (1) to experimental problems, the change in strain and the change in temperature need to be quantifiable and changed from a volumetric problem to a one-directional (length) problem. Therefore, Eq. (1) was derived to a third-order polynomial whose solution is defined as:

$$\alpha_L = \frac{1}{L}\cdot\frac{\partial L}{\partial T}. \tag{2}$$

In the solution for α_L the linear expansion coefficient, L is the reference length of the sample at initial temperature T_0; ∂L is the difference in length of the sample induced by temperature change, and $\partial T = T_1 - T_0$, where T_1 is the higher measured temperature.

The solution of Eq. (2) provides the basis for which α can be estimated at any given temperature from the change in sample length based on the reference length of the sample, in our study is the initial sample length prior to heating. The role of thermal expansion in thermoelastic stress is classically given by Timoshenko and Goodier (1970) such that thermal stress can be simplified and calculated by the following relation:

$$\sigma_t = \frac{\alpha E \Delta T}{(1-\nu)} \tag{3}$$

where σ_t is the tensile thermal stress (MPa), E is the Young's modulus (MPa), ΔT is the temperature differential (°C) and ν is the Poisson's Ratio. Through use of this formula, we can derive the instantaneous stress that a plane will experience as a result of an induced temperature differential. In order to be valid, the formula assumes that the plane on which the stress is acting is in thermal equilibrium before the thermal strain is developed through temperature change. Further, it is assumed there is no strain response as the plane is considered to be constrained and thermal stress is developed as a tensile stress. Applying Eq. (3), we can approximate the stress that thermal expansion can exert on a body. When coupled to the tensile strength of a material, a criterion for thermo-mechanical failure can be estimated using this relation. It should be noted that as thermal stress is released from cracking, elastic stress is nearly instantaneously dissipated. This then changes the bulk material properties and may result in a change of the material's thermal properties.

In this paper, we quantify the properties of the Rotokawa Andesite from thermomechanical analysis (TMA), differential scanning calorimetry (DSC), thermogravimetric analysis (TG), and porosity measurements. In conjunction, these methods can indicate the mechanical and chemical changes that a rock may experience at high temperatures. Mass loss or gain is measured by TG and the energy required by a thermochemical reaction is indicated by DSC, and these can be used to interpret changes in thermomechanical behavior over a given temperature range. From the results of our analysis, we develop an understanding of some of the constraints by which thermal stress may be manifest in rocks of the Rotokawa Andesite. The collected data are used in conjunction with previous studies on the physical properties of these andesites to build models to predict the role of thermal expansion under an induced thermal stress. The results are then discussed in relation to the geothermal reservoir from which the samples are sourced and the effect both natural and induced thermal gradients may have on the reservoir system.