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Impact of thermo-mechanical stimulation on the reservoir rocks of the geothermal system at Krafla, Iceland

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ABSTRACT

The controlled enhancement of fluid flow within a geothermal reservoir is a challenge as knowledge of stress distribution and rock response eludes us. One of the most common ways to improve fluid flow in a well, is through thermal stimulation. Here we investigate the influence of thermal stressing of basalt (present in the geothermal field of Krafla volcano, Iceland) on the development of thermal stresses and fracture creation leading to changes in rock permeability. We first measure the linear thermal expansivity of the basalt, noting that it increases slightly, ~linearly with temperature up to 750 ˚C. We tested the effect of heating/cooling cycles on basalt and noted that the permeability of the basalt tested was not affected by thermal stimulation (within the resolution of the permeability measurements), for the range of heating/cooling conditions, even after five cycles. Simple modelling of the experimental results shows however that small temperature changes can be sufficient to create thermal stresses that exceed the rocks' tensile strength at ambient pressures (not considering additional contributions from the local stress field in the system). We discuss the implication of these results, both for the development of laboratory methods and field site exploration.

1. INTRODUCTION

The flow capacity from a geothermal well and the commercial potential of a geothermal reservoir is dependent on the permeability of the reservoir (e.g. Murphy et al., 1981). To enhance the natural, near-well permeability of a reservoir, geoengineering methods such as fracking (e.g. Legarth et al., 2005; McClure and Horne, 2014; Miller, 2015; Tomac and Gutierrez, 2017; Zimmermann et al., 2011) or thermal stimulation (e.g. Grant et al., 2013; Siratovich et al., 2015b) have been developed to increase the presence of fractures that provide additional fluid pathways in reservoirs (e.g. Aqui and Zarrouk, 2011; Eggertsson et al., 2016; Heap and Kennedy, 2016; Lamur et al., 2017). Several factors may contribute to the generation of thermal stresses in rocks, such as anisotropic thermal expansions of minerals, thermo-chemical reactions and heterogeneous temperature gradients (e.g. Siratovich et al., 2015a). Anisotropy in thermal expansion is thought to be the main contributor to thermal cracking in igneous rocks (e.g. Browning et al., 2016; Siratovich et al., 2015a). Although thermal stimulation of wells has been a common practice for decades, and it has the potential to be a cheap way to enhance the fluid flow and be very beneficial, its impact on the magnitude of *in-situ* stress and extent of fracture opening remains difficult to ascertain (Flores et al., 2005).

In Iceland, thermal stimulation of wells is common (e.g. Axelsson et al., 2006). It is often performed upon well completion, before any flow tests have been made. Circulation loss has been monitored and used as a proxy for a well's permeability (Figure 1; Stefánsson et al., 1982). It has also been shown that thermal properties of the reservoir (as well as lithology) can influence injection capacity (Injection Index) of wells, depending on the temperature of the fluid that is being injected (Gunnarsson, 2011). Due to the high temperatures (>200 °C) of exploited geothermal reservoirs (e.g. Axelsson et al., 2014), the potential for high thermal gradients between the reservoir temperature and the temperature of the injection fluids is high and therefore, cracks are more likely to occur (Siratovich et al., 2015a). The induced thermo-elastic stress change (Eq. 1), occurring as a result of temperature change within the rock, is given as (Siratovich et al., 2015b; Timoshenko and Goodier, 1970):

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

σt = induced tensile thermal stress (MPa)
α = linear expansion coefficient (m/ (m K))
E = Young's modulus (MPa)
ΔT = temperature difference (°C)
ν = Poisson's ratio

Here, we assess the extent of thermal stimulation in wells drilled in a basaltic environment, using the results of laboratory experiments, conducted in the Volcanology and Geothermal Research Laboratory at the University of Liverpool. This focuses on the case of Krafla volcano, in North-East Iceland, where geothermal production has been ongoing since 1978 from a high temperature reservoir (reservoir temperature >200 °C). Geological investigation from drill-cuttings has revealed that the upper most part of the reservoir (<1000-1300

m) is primarily made up of basaltic lavas and hyaloclastites. At greater depths (>1000-1300 m) intrusions become more common (Mortensen et al., 2015).

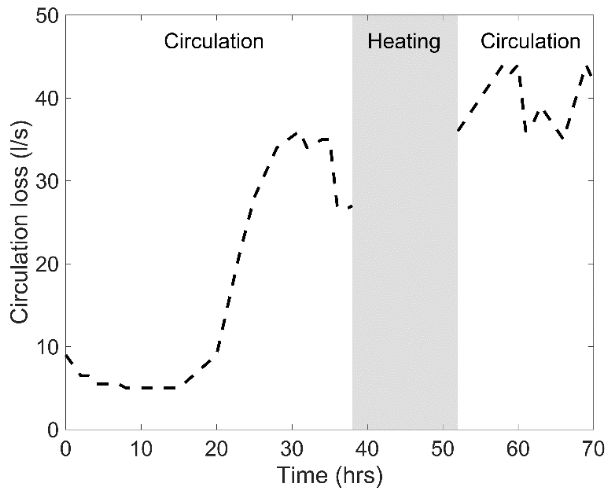

Figure 1. Circulation loss during thermal stimulation of well KJ-14 in Krafla, NE-Iceland (there is no loss during the heating phase). The stimulation of the well made it one of the most productive well in Krafla at that time (Stefánsson et al., 1982).

2. METHODS AND MATERIALS

To evaluate the magnitude of induced thermal stresses and evaluate changes in matrix permeability, we combine drilling reservoir data from Krafla with laboratory testing of basalt from Krafla. The material used for testing is a basalt erupted during the Mývatns fires in 1724-29 (Sæmundsson, 1991). Cylindrical core samples with a diameter and length of 25 mm were prepared for testing.

Experimental methods

The permeability of basalt samples (with 10% ±1 vol. % porosity) was measured using a benchtop permeameter. The permeability was measured by imposing a small pressure gradient where the flow of water was measured through the sample using a steady-state flow method. All measurements were conducted at a low confining pressure of 1 MPa to ensure fractures remained open (Lamur et al., 2017). To test the effects of thermal stimulation on the basalt, 9 cores were split into groups of 3 after permeability was measured. Each group was then heated at a steady rate of 5°C/min to set temperatures of 125 °C, 225 °C or 325 °C and held for 60 minutes. After that time, one core of each group was cooled in a bucket of water at ~20 °C, another was allowed to cool on the benchtop at ~20 °C and the third one was allowed to cool under a slow, controlled, cooling rate (~1 °C/min) in the furnace. Once the samples had cooled down, the permeability was re-measured. Then, the process was repeated for a further four heating/ cooling cycles and the permeability was measured again.

The thermal expansion of the basalt from Krafla was measured using a Netzsch TMA 402 F1 Hyperion Thermomechanical Analyzer (TMA). Following a baseline run, to accurately determine the thermal expansion of the sample assembly, the sample was heated up at a rate of 5 °C/min to 850 °C and cooled at the same rate. For the temperature range tested here, complementary simultaneous thermal analysis (combining the measurements of thermogravimetric analysis (TG) and differential scanning calorimetry (DSC) were carried out using a Netzsch STA 449 F1 Jupiter analyzer, to ensure that no reactions would occur and overprint the effects of thermal stressing on the porous network upon heating (Siratovich et al., 2015b).

Properties of Icelandic basalt

Estimates of stress induced by cooling rely on a knowledge of the rock mechanical properties (i.e., tensile strength, Young's modulus and Poisson's ratio), which have been presented for a large dataset of Icelandic basalt in a report to the Road Administration of Iceland (Table 1; Loftsson and Steingrímsson, 2010). For our sample set, the porosity of the basalt chosen falls within the anticipated range (Table 1), having porosity of 10% ±1% and tensile strength of 5-15 MPa (Loftsson and Steingrímsson, 2010). For the model, we use the values relevant to our samples for which the porosity was measured

Table 1. Mechanical properties of Icelandic basalt presented in Loftsson and Steingrímsson (2010) and thermal properties of the Krafla basalt (as measured here).

Measured rock property	Range of values from Loftsson and Steingrímsson (2010)	Chosen properties for model
Porosity	1 – 33 %*	10% ±1%
Uniaxial strength (UCS)	4 – 330 MPa*	-
Tensile strength (TS)	0.25 – 20 MPa*	5-15 MPa**
Young's modulus	2.22 – 43.48 GPa*	40 GPa**
Poisson's ratio	0.18 – 0.20*	0.2**
Average thermal expansion (α)	N/A	6.09 x10^{-6} (1/K) ***

*From (Loftsson and Steingrímsson, 2010).
** Representative value chosen.
***Results presented in Figure 2.

3. RESULTS

Thermal expansivity determination

The linear thermal expansion and contraction (α) was calculated from change in length of the sample as it was heated 5 °C/min for the thermomechanical analyses (Figure 2). We note that the expansion was ~linear as a function of temperature to 500 °C before stabilizing.

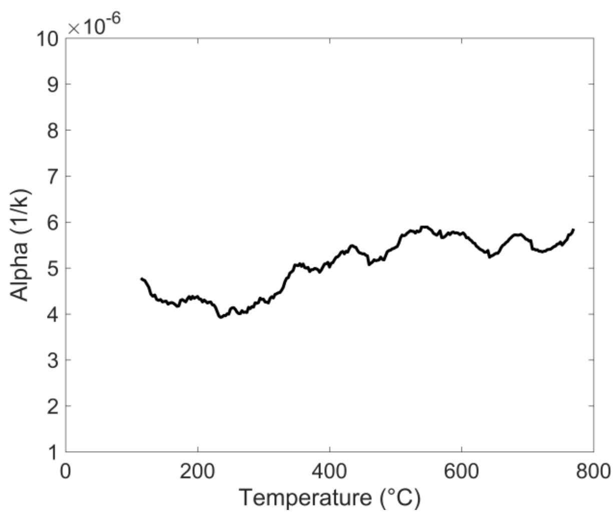

Figure 2. Thermomechanical analysis, showing the linear thermal expansion of basalt at 5 °C/min.

Thermally induced tensile stress modelling

By using the thermal properties of the basalt from Krafla (Fig. 2), and its mechanical properties reported in Table 1, we can constrain the thermo-elastic stress resulting from cooling of reservoir rock via Equation 1 (Figure 3). For comparison, we show the range of tensile strength of the Icelandic basalt from Loftsson and Steingrímsson (2010). We observe that changes in the Young's modulus can have significant effects on the tensile stress induced by cooling; the analysis suggest that 15-20°C of cooling is needed to induce thermal cracks in rocks with high Young's modulus, whereas as much as 25-30 °C cooling is needed in rocks with lower Young's modulus. This cooling range would further depend on the local stress conditions (i.e., pore pressure and local stress anisotropy) in the reservoir (not assessed here).

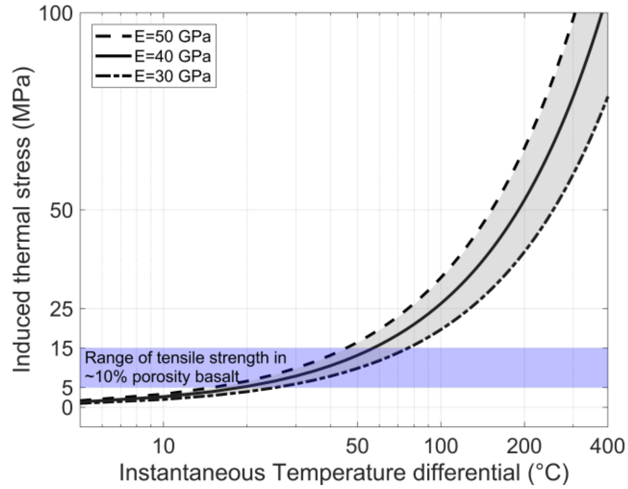

Figure 3. Model results of thermally induced tensile stress changes resulting from cooling of the basalt from the Mývatns Fires. The range of tensile strength of basalt containing 10% porosity is also shown in blue.

Impact of thermal stressing on basalt permeability

To investigate further the potential effect of thermally stressing rocks around wells with imposed temperature change, basalt cores were thermally stressed with different temperatures and cooling rates. During well construction and operation, temperature fluctuations occur in addition to thermal stimulation methods. The data shows that the changes in permeability following thermal stressing was trivial (Table 2); and thus, any changes may have remained within the resolution limit of permeability determination for the conditions tested.

Table 2. Impact of thermal stress cycles on the permeability of basalt. Thermal stressing was undergone by heating to 125, 225 or 325 °C and cooling to room temperature in water (rapid), in air or in a furnace (under slow, controlled, cooling rate).

Set temperature (°C)	Sample	Cooling environment	Permeability (m^2)		
			Initial	1 cycle	5 cycles
125	Basalt_6w	Water	$1.2x10^{-15}$	$1.1\ x10^{-15}$	$1.3\ x10^{-15}$
	Basalt_3b	Air	$4.0x10^{-15}$	$4.0\ x10^{-15}$	$4.0\ x10^{-15}$
	Basalt_7f	Furnace	$5.4\ x10^{-15}$	$5.1\ x10^{-15}$	$5.2\ x10^{-15}$
225	Basalt_13w	Water	$1.7\ x10^{-15}$	$1.5\ x10^{-15}$	$1.5\ x10^{-15}$
	Basalt_14b	Air	$2.6\ x10^{-15}$	$2.3\ x10^{-15}$	$2.5\ x10^{-15}$
	Basalt_12f	Furnace	$5.2\ x10^{-15}$	$4.4\ x10^{-15}$	$4.8\ x10^{-15}$
325	Basalt_9w	Water	$4.7\ x10^{-16}$	$4.5\ x10^{-16}$	$4.9\ x10^{-16}$
	Basalt_2b	Air	$3.2\ x10^{-15}$	$3.9\ x10^{-15}$	$5.1\ x10^{-15}$
	Basalt_4f	Furnace	$5.7\ x10^{-15}$	$5.0\ x10^{-15}$	$5.4\ x10^{-15}$

4. DISCUSSION AND CONCLUSIONS

A better understanding of the magnitude and extent of tensile stresses generated by thermal stimulation will improve our understanding of reservoir geoengineering to increase fluid flow and energy production. Thermal stimulation may induce a new fracture when the tensile stress imparted by contraction from the imposed temperature change exceeds the tensile strength of the rock. The presence of pressurized fluids in vesicles and cracks, and the anisotropy of the local stress field may alleviate the magnitude of thermal stress needed to fracture the rock. If we do not consider this local stress, we find in our model of thermal stress (Fig. 3) that small changes in temperature can induce thermal stresses greater than the lower limit of tensile strengths. Yet, we found that permeability of the basalt was not changed when subjected to thermal stressing; we surmise that the nature of thermal stimulation tests commonly conducted in the laboratory may not fully mimic the nature of thermal stimulation from fluid injection in a borehole. Even though these tests are very helpful in the description of the material response to temperature changes, these tests are conducted on a cylindrical sample, free to expand and contract during heating/cooling cycles, without being constricted (as it would be in a natural environment). We posit that further experimental considerations may be required to widen the applicability of such tests. It remains that the permeability of geothermal reservoirs is certainly strongly influenced by fractures, but the influence of thermal stressing – as a trigger to generate new fractures or open pre-existing ones – still deserves close attention in order to develop accurate methods to efficiently enhance fluid flow within reservoirs in a controlled manner.

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