

Numerical modeling of thermal stimulation for geothermal core studies

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1 INTRODUCTION

We present the results of numerical simulations of laboratory experiments to give insight into the role of thermal shocking on geothermal reservoir rocks. Thermal stimulation is a reservoir permeability enhancement technique applied to commercial geothermal reservoir rocks to enhance fluid injection capabilities for spent power plant working fluids. The process is well known to enhance permeability, but the thermodynamic and physical constraints of the process are less certain. In an attempt to constrain the interaction and the ideal conditions that lead to permeability enhancement, experimental procedures were carried out to mimic the conditions that a reservoir rock would experience during a thermal stimulation using temperature differentials ranging from 50-300°C. Samples underwent thermal gradients under controlled laboratory conditions and were characterized for the changes to permeability, porosity, ultrasonic velocities, dynamic elastic moduli and petrological changes. The thermal stimulation was simulated in a *FLAC* (Itasca 2016) thermal numerical model to investigate the nature of the thermally induced changes in the sample. The development of this model allows us to investigate the relationship between geological characteristics and the ability to thermally stimulate any type of rock. The results indicate that numerical thermal shocking experiments are corroborated by laboratory-based results. The implication of this study is that the numerical models present an insight into the conditions and constraints under which thermal stimulation can enhance permeability that could not be gained purely through laboratory-based studies.

2 DESIGN AND ANALYSIS

2.1 Mechanical and Thermal Constitutive Models

The numerical technique developed by Villeneuve et al. (2012) is a mechanical-only technique and uses the bilinear-ubiquitous joint strain-softening constitutive model in *FLAC*, as given in Villeneuve et al. (2012). The thermal-mechanical option in *FLAC* was used to allow coupling of thermally induced strains and stresses with mechanical behavior of the material. This requires input of mineral-specific constitutive properties for both thermal and mechanical models (Tables 1 and 2, respectively). These values, based on literature values, as given in the notes below the tables, are implemented as ranges in the numerical model on a mineral-by-mineral basis. In the case of pyroxene, two different species occur in the Rotokawa Andesite, and their thermal properties are input individually due to the large difference between the two. They are treated as the same mineral with respect to mechanical properties. Cleavage parallel and cleavage perpendicular strength and stiffness differ in chlorites, similar to micas in Villeneuve et al. (2012). The ubiquitous joint model in *FLAC* was used for the chlorite to represent these two strength and stiffness orientations. Water is modelled as an elastic medium to account for the hydrostatic pressure that develops in water-filled voids. Thermal parameters and stiffness parameters are used, and although water cannot take shear strains, a very small value is used to ensure numerical stability.

Table 1. Parameters at 293 K for thermal induction constitutive model.

Mineral	Conductivity (Wm ⁻¹ K ⁻¹)	Linear Expansion (10 ⁻⁶ K ⁻¹)	Specific Heat (Jkg ⁻¹ K ⁻¹)
Plagioclase	1.53-2.36 ^a	5.8-7.4 ^b	730-757 ^c
Pyroxene (augite)	3.83 ^a	7.1-12.2 ^d	670 ^c
Pyroxene (enstatite)	4.17-4.98 ^a	10.2-12 ^d	787 ^c
Chlorite	4.35-6.2 ^a	5.77-10.9 ^c	760-770 ^c
Water	0.6 ^f	1 x 10 ⁻⁷ or 69 ^f	4200 ^f

Data in Table 1 sourced as follows: ^aHorai 1971; ^bArndt & Häberle 1973; ^cWaples & Waples 2004; ^dFei 1995 and Hugh-Jones 1997; ^ePawley et al. 2002; ^fWeast 1975.

Table 2. Parameters for mechanical strain-softening constitutive model.

Mineral	Cohesion (MPa)		Coefficient of Friction		Tensile Strength	Elastic Moduli (GPa)		Strain reduction
	Peak	Residual	Peak	Residual	(MPa)	G (Shear)	K (Bulk)	$\epsilon \times 10^{-3}$
Plagioclase	80-125 ^a	4-6 ^a	0.12-0.59 ^b	0.8 ^c	36 ^d	28-33 ^c	55-65 ^c	2.4-4.4 ^a
Pyroxene	75-88 ^f	4 ^f	0.006-0.02 ^g	0.74 ^g	23 ^h	33 ⁱ	56 ⁱ	2.2-2.6 ^f
Chlorite (parallel)	95 ^j	2 ^j	0.53 ^b	0.68 ^c	4.5 ^d	53 ^k	87 ^k	8.3 ^j
Chlorite (perp.)	48 ^j	5 ^j	0.78 ^b	0.43	39 ^d	15 ^l	87 ^k	16.3 ^j
Water	-	-	-	-	-	1.3 x 10 ^{-5 m}	2.2 ⁿ	-

Data in Table 2 sourced as follows: ^aDerived according to Villeneuve (2008) from data in Belikov 1967; ^bDerived according to Villeneuve (2008) from data in Horn & Deere 1962; ^cMorrow et al. 2000; ^dVilleneuve 2008; ^eBelikov 1967; ^fDerived according to Villeneuve (2008) from data in Wuerker 1956; ^gDerived according to Villeneuve (2008) from data in Luo 2009; ^hWuerker 1956; ⁱWoirgard & Gueguen 1978; ^jDerived according to Villeneuve (2008) from data in Coates & Parsons 1966; ^kPawley et al. 2002; ^lDerived according to Villeneuve (2008) from data in Pawley et al. 2002; ^mKorenchenko & Beskachko; ⁿWeast 1975.

2.2 Mechanical and Thermal Stimulation Simulations

The sample size used in the laboratory has a 20 mm diameter and was 40 mm high for both mechanical and thermal testing. Using the technique in Villeneuve et al. (2012) this gives a minimum element size of 0.2 mm. The simulated Rotokawa Andesite (Fig. 1) was built with geological characteristics for sample RK27_L2_23.3A, from a depth of approximately 2000 m, with the following mineralogy, grain size and grain shape:

- Plagioclase (50% albite, 50% labradorite): 35%, 1.4-2mm, eu- to subhedral
- Pyroxene (augite, clinopyroxene): 5%, 0.2-1mm, an- to euhedral
- Pyroxene (enstatite, orthopyroxene): 5%, 0.2-1mm, eu- to subhedral
- Chlorite: 50%, 0.2mm, euhedral
- Voids (water filled): 5%, 0.2-0.6mm, elongate

The numerical mechanical testing was conducted as in Villeneuve et al. (2012). The numerical thermal stimulation was conducted by heating the sample at the same rate as in the laboratory. A temperature of 293 K was initialized, and then the sample was heated by applying a flux of 547.2 Ws-1m-2 at the sample boundary to produce a temperature increase of 2 K/min to 598 K. The sample was allowed to dwell at 598 K for two hours to ensure that the temperature in the sample had equilibrated and that the thermal and mechanical stresses and strains had also equilibrated. The sample was then quenched by applying a series of flux values to produce temperature decreases of various rates along the entire boundary, back down to 293 K. Temperature of the sample boundary was measured at element (1,1). Axial strain was measured at the center top of the sample and lateral strain was measured as an average of the top quarter, middle and bottom quarter.

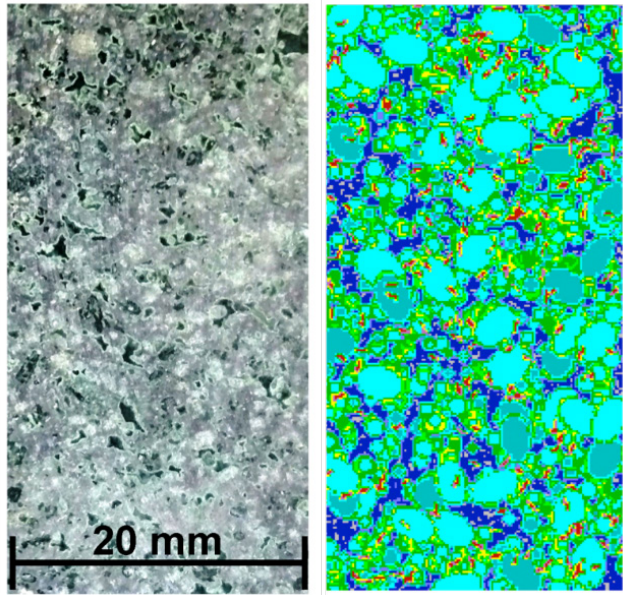


Figure 1. Rotokawa Andesite: laboratory sample (left); simulated sample (right; red = void; dark blue = chlorite; green = pyroxene; teal = feldspar).

3 RESULTS AND DISCUSSION

The simulated rock texture is similar to the rock texture of the laboratory sample (Fig. 1). The mechanical validation shows that the simulated RK27_L2_23.2A has the same strength (UCS: 102-108 MPa) as the laboratory sample (UCS: 105 MPa; Siratovich et al. 2014). The elastic moduli are both higher in the simulated samples (E: 69-71 GPa, ν : 0.33-0.36) than in the laboratory sample (E: 31.2-38.9 GPa, ν : 0.19-0.23), however they are in the appropriate order of magnitude and for this stage in development, are sufficiently close.

The stimulation results (Fig. 2) show the development of connected fractures across the sample. This is similar to the generation of connected porosity (microfractures) observed in the samples stimulated in the laboratory (Siratovich et al. 2015). The fractures tend to connect the pre-existing voids, and preferentially develop along grain boundaries (Fig. 2, right, inset). This is also what we observe in samples stimulated in the laboratory and in the literature (for example: Fredrich & Wong 1986). Figure 2 also highlights some of the value obtained by numerically modelling the stimulation process. We can observe the fracture patterns at the grain scale and examine the development of the fractures with respect to element yield type (Fig. 2, left), minerals (Fig. 2, right), stress state, displacements, temperature variations, etc., all of which can be plotted, queried and output to spreadsheets for quantitative analysis.

4 CONCLUSIONS

We have shown that numerical simulation of thermal stimulation can reproduce the behavior observed in the laboratory. The advantage of the numerical simulation is that it provides the ability to explicitly model mineral grains. This gives us the ability to investigate the impact of changes in mineralogy, grain size and texture on thermal stimulation. The numerical simulation also allows us to examine the behavior at the micro-scale at different stages in the stimulation: the temperature variations, stresses, strains and displacements that lead to the behavior observed at the macro scale.

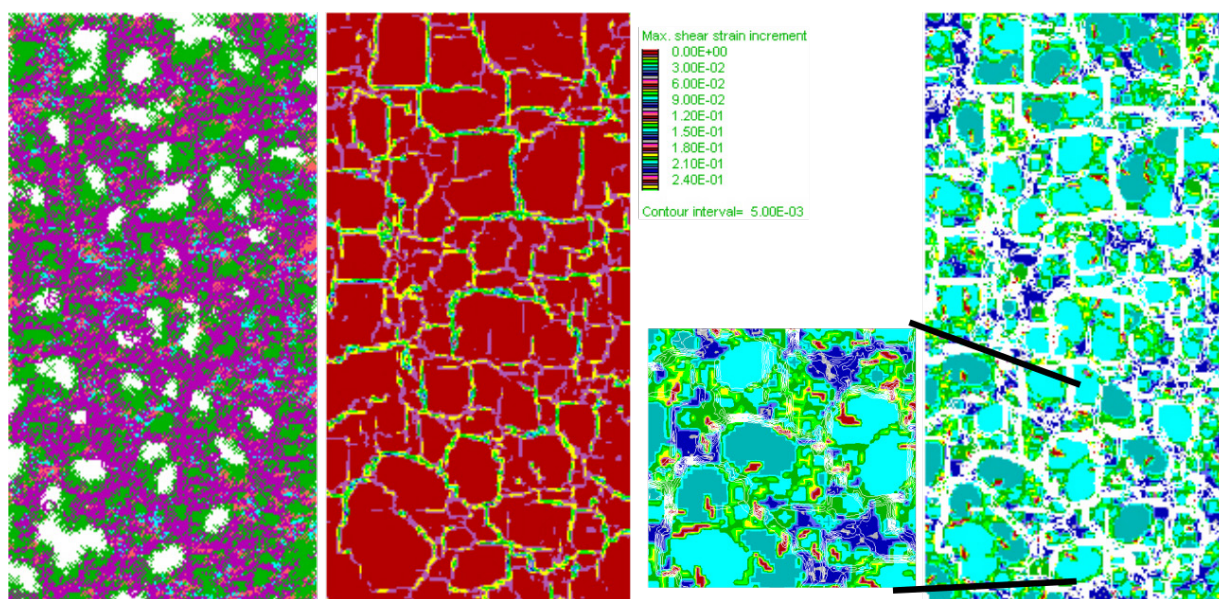


Figure 2. Modeled Rotokawa Andesite post quenching: failed elements (left); shear strain (center; strain interval $5e-3$); shear strain (white; strain interval $5e-3$) overlaid on the minerals (right, with inset; red = void; dark blue = chlorite; green = pyroxene; teal = feldspar).

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