Enhancing permeability by multiple fractures in the Krafla geothermal reservoir, Iceland

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Keywords: Fracture permeability, Storage capacity, Krafla geothermal reservoir.

ABSTRACT

The presence of fractures in hydrothermal systems influences the storage capacity and efficiency of fluid flow necessary for successful and sustained exploitation for geothermal energy production. The magmatic-hydrothermal system at Krafla Volcano, North-East Iceland, has been exploited by Landsvirkjun National Power since 1977 to generate electricity. Here, to gain insight on the permeability of the reservoir rock, we present results of laboratory experiments conducted to evaluate the effects of multiple fractures on the permeability and porosity of basaltic rocks (with 10-21% initial porosity) collected at Krafla. A hydrostatic cell was used to measure the permeability and pore volume changes of intact rocks as a function of effective pressure (5-100 MPa). The samples were then fractured using Brazilian tensile tests and permeability measurements were repeated under the same range of conditions. Finally, the samples were fractured a second time and the permeability was measured anew. The results show that the generation of the first macro-fracture induced the most significant permeability and porosity changes. The permeability increase due to the presence of a macro-fracture is highest for the densest samples, with a porosity of <15%. The generation of a second fracture imparts little additional effect on permeability across the range of porosities tested. The findings show that the effective pressure is a key control on the efficacy of fluid flow in intact and especially, fractured rocks.

1. INTRODUCTION

The porous networks of crustal rocks are capable of storing high-pressure and temperature fluids, extracted for geothermal energy production (Gudmundsson, 1995). The storage capacity is thus directly related to the porosity of the rock, in particular the connected porosity (e.g. Siratovich et al., 2014). Hence, permeability within exploited geothermal fields has an important control on both productivity and the sustainability of fluid flow within the reservoir. The development of permeability (whether natural or induced) has a great impact on the success, magnitude, and sustainability of energy production (e.g. Mock et al., 1997; Zimmermann et al., 2009).

The architecture of the porous network of rocks and, as a result, permeability varies widely (e.g. Brace, 1980; Norton and Knapp, 1977; Paterson and Wong, 2005). This is especially the case for volcanic rocks, as they have undergone complex deformation histories during their formation (Ashwell et al., 2015; Kendrick et al., 2013). It has been suggested that there is a porosity change point (15~20%) above which, the permeability is primarily controlled by pores and below which, by fractures (Klug and Cashman, 1996). This owes to the relative tortuosity and pore throat size of the variably constructed porous networks of dense and porous rocks (Farquharson et al., 2015). As a result, the permeability of dense rocks (<15% porosity) can be more strongly influenced by the generation of macro-fractures as it decreases the tortuosity of fluid flow through fractures (Lamur et al., 2016).

Geothermal exploitation relies heavily on the presence of fractures to optimise fluid flow and energy generation. During drilling operations, a number of methods have been applied to enhance the extent of permeable fractures, whether through fracking (McClure and Horne, 2014; Miller, 2015; Zang et al., 2014) or thermal stimulation (Grant et al., 2013; Siratovich et al., 2015). However, in high-temperature, high-enthalpy geothermal reservoirs, where the rock may exhibit pseudo-plastic behaviour (e.g. Violay et al., 2012), it is commonly assumed that fractures would not remain effectively opened for long periods of time (e.g. Scott et al., 2015). This can be overcome if the rock is kept fragmental if stress is sufficiently high (e.g. Lavallée et al., 2013) or by keeping temperature low, thus thermally contracting the rock (e.g. Siratovich et al., 2015).

The hydrothermal system of Krafla volcano, North-East Iceland, has been a source of extensive exploitation for geothermal energy production since 1977 (Landsvirkjun, 2016). Geological investigation of drilling products (cores and cuttings) has revealed that the upper 1300 m of the Krafla reservoir is primarily made up of basaltic lavas and hyaloclastite. At depths below 1300 m, the reservoir is made up of intrusive volcanics, primarily gabbro and felsite (e.g. Bodvarsson et al., 1984; Mortensen et al., 2014). Recent drilling activity during the Iceland Deep Drilling Project (IDDP) has revealed the presence of a shallow rhyolitic magma body at 2100 m, powering the hydrothermal system (Elders et al., 2011; Zierenberg et al., 2013), which has now been imaged using geophysical inversion (Schuler et al., 2015). The combined volcanological and geothermal interest for this system has recently pushed the organisation of the Krafla Magma Drilling Project (KMDP) – a joint international effort aiming to further our understanding of the potential, limitations, sustainability and dangers of clean magma energy exploitation (Eichelberger et al., 2015). Such activities will also further our understanding of magma-hydrothermal systems to improve volcanic hazard assessment (Björnsson et al., 2007).

Here, we present results of laboratory experiments, conducted in the Volcanology and Geothermal Research Laboratory at the University of Liverpool, to evaluate the effect of multiple induced tensile fractures on the permeability of basaltic rocks from the Krafla volcanic/geothermal field in North-East Iceland.

2. METHODOLOGY

To evaluate the impact of multiple fractures, we combined permeability measurements with indirect Brazilian tensile tests. The tests were carried out on basalt lava, erupted during the 1724-29 Mývatn fires (Ármannsson et al., 2014), collected near the drilling platform of KV-01, during a field campaign at Krafla volcano in the summer 2015.

The samples prepared for this study had a 2:1 aspect ratio, with a diameter of 26 mm and thickness of ~13 mm. The connected porosity was determined using an AccuPyc 1340 He-pycnometer from Micromeritics. The chamber used was 35 cm^3, which provides a volume determination accuracy for the sample of ±0.1%.

The initial permeability of the cylindrical samples was measured in a hydrostatic pressure cell from Sanchez Technologies (Figure 1) following Darcy's Law. The cylindrical sample was placed inside a rubber jacket and the rock permeability was measured using water by imposing a pressure gradient of 1.5 MPa across the sample (upstream: 2 MPa; downstream: 0.5 MPa) at an average pore pressure of 1.25 MPa for a range of confining pressures (5-100 MPa) using silicon oil. Thus the measurements were done for a range of effective pressures (effective pressure = confining pressure – pore pressure) that cover, and extend beyond, the conditions of the Krafla geothermal reservoir. At each confining pressure, two measurements are made with the low and high flow rate value recorded. The porosity change undergone by compaction of the samples during confinement to different pressures was assessed by monitoring the amount of water expelled from the samples back into the volumometer of the pumps. The accuracy of the volumometer on the pump is 0.002 ml and the volume of water displaced from the samples during confinement ranges between 0.020 and 0.100 ml. Hence the accuracy of each measurement is 2-10 %, depending on the volume of water displaced (relating to the absolute porosity) and the accuracy of this method for the calculation of porosity variation is 4-20%. Before and after each test, the sample was dried in an oven at 75 °C.

To induce tensile fractures through the samples, the Brazilian tensile testing method was employed. To break the samples, the cylindrical sample was loaded diametrically in a 5969 Instron uniaxial press at a rate of 10^{-3} s^{-1}. To ensure that the samples would not disintegrate during tensile fracturing, the samples were carefully wrapped in electrical tape around the circumference.

After sample failure, the tape was removed and the porosity was measured before jacketing the sample and measuring the permeability anew. A second set of fractures was then imparted, perpendicular to the first fracture in the samples. This time, however, the sample was left in the rubber jacket during loading in the press to ensure it remained coherent. After sample failure, the permeability was measured once again under the same range of conditions as detailed above, and finally the sample was removed from the jacket and porosity was measured

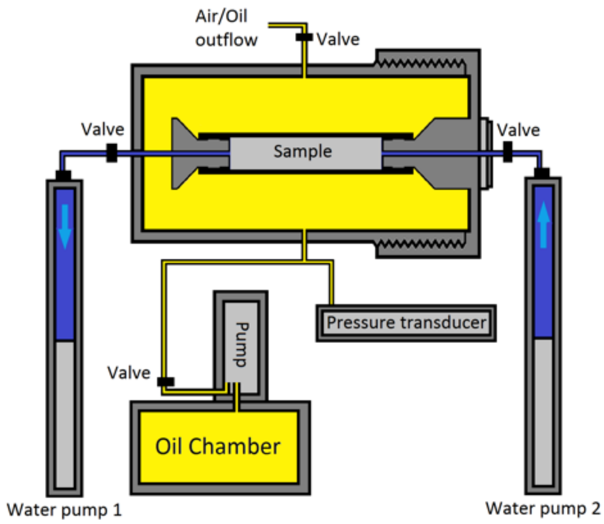

Figure 1: Schematic of the Sanchez permeameter at the University of Liverpool. The rock permeability was measured using water by imposing a pressure gradient of 1.5 MPa across the sample at an average pore pressure of 1.25 MPa (upstream: 2 MPa; downstream: 0.5 MPa) for a range of confining pressures (5-100 MPa). The porosity variation was measured by displacement of water back into the volumometer of the pump.

3. RESULTS

3.1 Brazilian tensile testing

The porosity of the samples tested in this study ranges from 10.9% to 21.3% and the density is 2.40-2.74 g/cm^3 (Table 1). The results of the Brazilian tests show an inverse correlation between the tensile strength and the porosity of the rocks (Table 1) as seen in other studies on various lithologies (e.g. Aydin and Basu, 2006; Palchik and Hatzor, 2004).

Table 1: Connected porosity of intact and fractured (F1; 1 fracture, F2; 2 fractures) samples, density and peak strength results.

Sample name	Porosity (%)			Density (g/cm^3)	Peak strength (MPa)
	Intact	F1	F2		
KB-04	15.9	16.0	16.7	2.57	11.5
KB-08	13.5	13.6	14.3	2.66	18.3
KB-10	14.8	15.1	16.3	2.60	18.4
KB-14	12.9	13.1	14.3	2.68	19.9
KB-19	10.9	11.2	11.3	2.74	20.0
KB-20	21.3	21.4	23.7	2.40	8.1

The first tensile failure, generated by Brazilian testing, generally fractured the sample through the centre (shown as the near-horizontal fractures on Figure 2). The fracture was found to be sharp and centred for the densest samples (<15% pores), but undulating and less central for the more porous samples. The geometry of the second tensile fracture (near-vertical in Figure 2) was also dependent on the sample porosity; that is, the second fracture is straight in the densest rocks (<15% pores; Figure 2).

3.2 Storage capacity as a function of effective pressure

The storage capacity of fluid-filled rocks may vary as a function of effective pressure (Wong and Baud, 2012). Here, we combine helium-pycnometry measurements and the monitored data from the volumometers in the hydrostatic pressure vessel to constrain the evolution of porosity during confinement (Figure 3). In doing so, we assume that the connected porosity at an effective pressure of 5MPa is the same as that measured via helium pycnometry (0 MPa).

The data shows that the storage capacity of the intact samples may decrease by 2-3% (in absolute porosity value) by increasing the effective pressure from 5 to 100 MPa (Figure 3; 50 MPa for weaker sample KB-20 which could not sustain 100 MPa). The presence of a single fracture increases the porosity of the sample. An

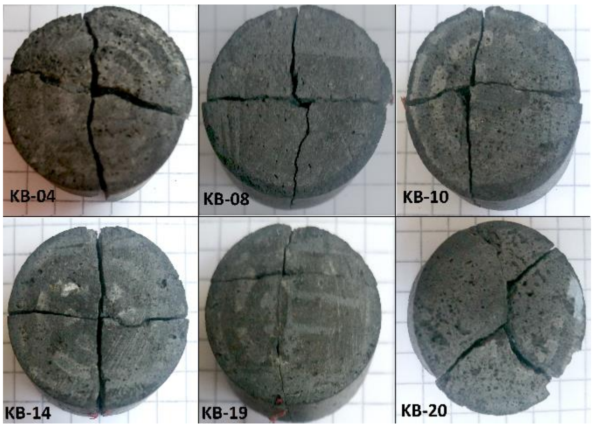

Figure 2: Photographs of the samples. The vertical fracture in all of the photos is the first fracture generation, and the horizontal fracture is the second generation. The samples are 26 mm in diameter.

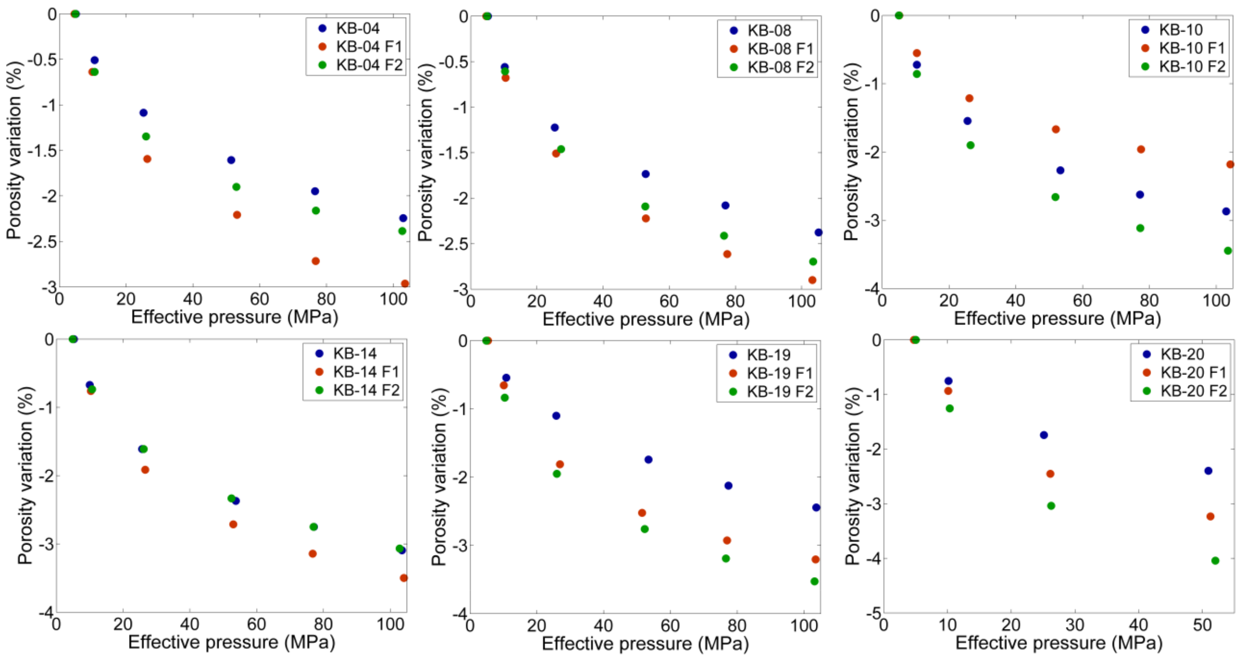

Figure 3: Porosity variation from the initial porosity (Table 1) for intact rock (blue) and samples with 1 fracture (red) and 2 fractures (green) as a function of effective pressure. Note that the scale of each graph varies.

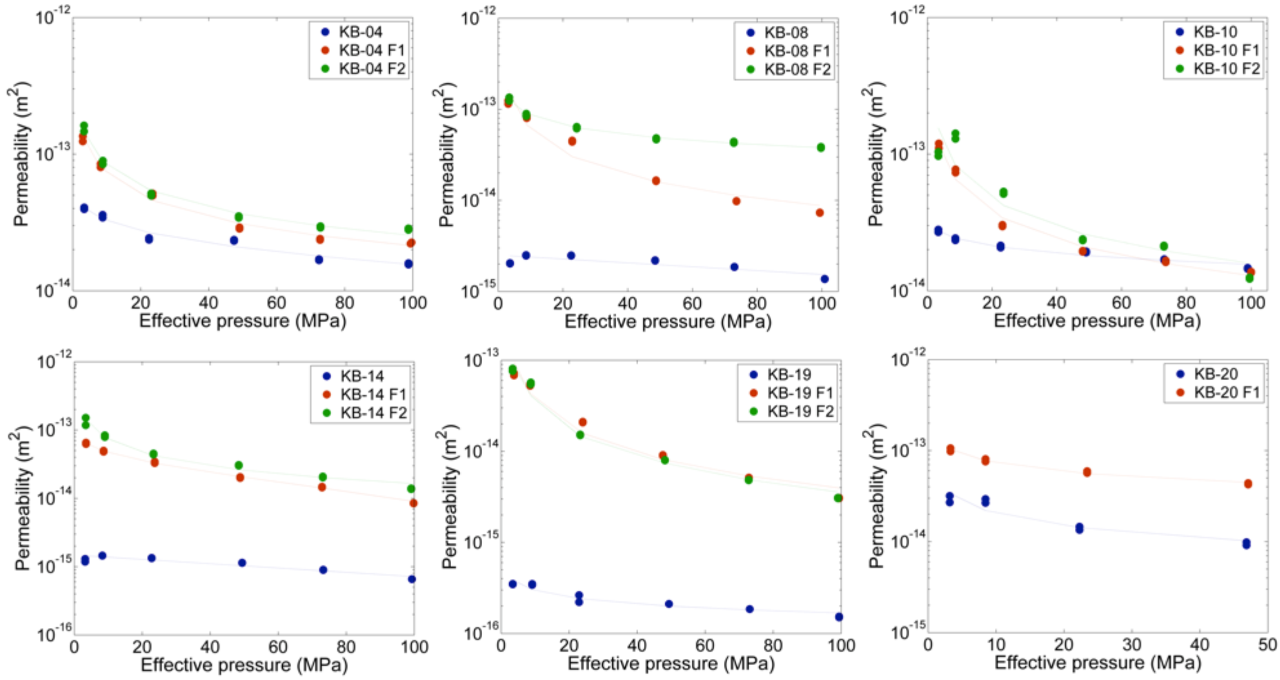

Figure 4: Permeability variation of intact rock (blue) and samples with 1 fracture (red) and 2 fractures (green) as a function of effective pressure. The permeability measurements show 2 points at each pressure step for each sample, this represents the maximum and minimum possible permeability values during the measurement given variation in flow rate. This variability is higher in the most permeable samples. Note that the scale of each graph varies.

increase in effective pressure from 5 to 100 MPa is found to decrease the porosity of the fractured samples by approximately 2-4% (Figure 3). Yet, we find that the samples do not all respond in the same way; for instance, in sample KB-10, the connected porosity in the presence of one fracture is maintained to relatively high effective pressure.

The porosity of samples hosting two fractures seems to show little difference to those harbouring only one fracture (Figure 3). The exception is the most porous sample KB-20, which lost small fragments during the second fracture generation. This loss of material resulted in a different initial porosity (Table 1; at effective pressure of 0 MPa) and a different porosity evolution as the effective pressure was increased. This sample is therefore excluded from further considerations of porosity-permeability evolution with pressure (i.e., it is not displayed in Fig. 4).

3.3 Permeability as a function of effective pressure

The permeability of rocks varies as a function of fracture density (e.g. Lamur et al., 2016) and confining pressure (Alam et al., 2014; Walsh, 1981). Here, we present permeability measurements on intact and fractured basaltic rocks. The permeability of the intact samples tested ranges between 10^{-13} and 10^{-16} m^2. The permeability of the rocks is constrained to decrease nonlinearly with an increase in effective pressure (Figure 4), due to the closure of micro-cracks; in some cases, permeability may decrease by ca. three orders of magnitude by increasing the effective pressure from 5 to 100 MPa. The permeability of the intact rocks increases non-linearly with porosity (Figure 5) as previously described (e.g. Ashwell et al., 2015; Bourbie and Zinszner, 1985; Farquharson et al., 2015; Heap et al., 2015; Kendrick et al., 2013; Kushnir et al., 2016; Lamur et al., 2016; Mueller et al., 2005; Saar and Manga, 1999; Schaefer et al., 2015; Stimac et al., 2004).

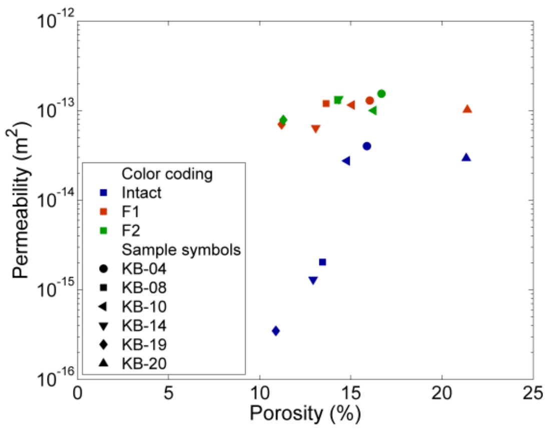

Figure 5: Permeability as a function of porosity for the initial and fractured basaltic rocks tested in this study. The permeability values plotted were obtained at an effective pressure of 5 MPa. Despite a wide range of permeability values for the intact samples across the porosity range tested, the fractured samples have a narrow range of permeability.

The presence of one macro-fracture induced through the samples has a net impact on the permeability of 0.5 to almost 3 orders of magnitude. This influence is greatest in lowest porosity samples (<15% pores). The generation of a second fracture does not appear to influence the permeability of the rocks further, despite creating more fracture surface area and increasing porosity (Table 1). This observation remains valid over the range of effective pressures tested; we note an exception with the case of sample KB-08, for which the second fracture seems not to close adequately with an increase in effective pressure, resulting in a permeability about 1 order of magnitude higher than the single-fractured sample at 100 MPa confining pressure (Figure 4).

4. DISCUSSION

A detailed knowledge of the storage capacity and permeability of reservoir rocks is crucial to improve the utilisation of geothermal resources and to maximise energy production. The experimental work carried out here sheds light on the efficiency of fluid flow through the permeable porous network of the basaltic rocks present in the Krafla geothermal system. The study shows that the porosity and permeability of rocks are nonlinearly influenced by the effective pressure exerted in the system, so permeability may be increased by controlling the pressure of the fluid injected into the hydrothermal system. Generation of a macro-fracture through the samples enhances the permeability of the rocks; the presence of a second perpendicular fracture however, does not impact the permeability further; though this may not necessarily be the case when rocks are pressurised in anisotropic stress fields where the presence of a second fracture may favour slight displacement/misalignment of the fragments, which may leave gaps in the rock to permit extensive fluid flow. We find that in dense rocks (with porosity <15%) permeability is significantly increased by the presence of a fracture (Figure 5); this may be explained by the greater decrease in the tortuosity of the porous network by inducing a fracture in dense rocks (e.g. Farquharson et al., 2015). Upon increasing the effective pressure, the fractures shut and permeability decreases; the initially more porous rocks (>15%) are able to attain a permeability more similar to their intact rock counterparts (Figure 4). The higher magnitudes of porosity and permeability decrease as a function of effective pressure for the fractured rocks (compared to intact rocks) suggests that fracture closure underlies the densification of rocks with confinement.

The laboratory measurements provided here offer a first step in the constraint of the storage capacity and permeability of the geothermal reservoir at Krafla volcano. However, it remains that the results do not account for complexity arising from the effect of high-temperatures, or complications that result from fluid flow in hot rocks such as the effects of dissolution and precipitation. Such descriptions are subject of ongoing work as part of the IDDP and KMDP projects.

5. CONSLUSIONS

The experimental study describes the influence of multiple fractures on the storage capacity and efficiency of fluid flow in basaltic rocks found in the geothermal system at Krafla volcano, Iceland. The data shows that the generation of the first macro-fracture has the greatest impact on enhancing the permeability of rocks, and that subsequent fractures do little to further increase fluid permeability. We find that effective pressure is an important control on the porosity and permeability of the rocks tested, and that it serves to primarily close micro- and macro-fractures, important in regulating fluid flow.

REFERENCES

Alam, A. K. M. B., Niioka, M., Fujii, Y., Fukuda, D., and Kodama, J.-i., Effects of confining pressure on the permeability of three rock types under compression: International Journal of Rock Mechanics and Mining Sciences, v. 65, (2014), p. 49-61.

Ármannsson, H., Fridriksson, T., Gudfinnsson, G. H., Ólafsson, M., Óskarsson, F., and Thorbjörnsson, D., IDDP—The chemistry of the IDDP-01 well fluids in relation to the geochemistry of the Krafla geothermal system: Geothermics, v. 49, (2014), p. 66-75.

Ashwell, P. A., Kendrick, J. E., Lavallée, Y., Kennedy, B. M., Hess, K. U., von Aulock, F. W., Wadsworth, F. B., Vasseur, J., and Dingwell, D. B., Permeability of compacting porous lavas: Journal of Geophysical Research: Solid Earth, v. 120, no. 3, (2015), p. 2014JB011519.

Aydin, A., and Basu, A., The use of Brazilian Test as a Quantitative Measure of Rock Weathering: Rock Mechanics and Rock Engineering, v. 39, no. 1, (2006), p. 77-85.

Björnsson, A., Sæmundsson, K., Sigmundsson, F., Halldórsson, P., Sigbjörnsson, R., and Snæbjörnsson, J. Þ., Geothermal Projects in NE Iceland at Krafla, Bjarnarflag, Gjástykki and Theistarreykir - Assessment of geo-hazards affecting energy production and transmission systems emphasizing structural design criteria and mitigation of risk: Landsvirkjun, (2007).

Bodvarsson, G. S., Pruess, K., Stefansson, V., and Eliasson, E. T., The Krafla Geothermal Field, Iceland: 2. The Natural State of the System Water Resource research, v. 20, no. 11, (1984), p. 14.

Bourbie, T., and Zinszner, B., Hydraulic and acoustic properties as a function of porosity in Fontainebleau Sandstone: Journal of Geophysical Research: Solid Earth, v. 90, no. B13, (1985), p. 11524-11532.

Brace, W. F., Permeability of crystalline and argillaceous rocks: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 17, no. 5, (1980), p. 241-251.

Eichelberger, J., Carrigan, C., Markusson, S., and Lavallée, Y., Clean magma energy for the North, The 2015 Arctic Energy Summit: Fairbanks, Alaska, USA, (2015).

Elders, W. A., Friðleifsson, G. Ó., Zierenberg, R. A., Pope, E. C., Mortensen, A. K., Guðmundsson, Á., Lowenstern, J. B., Marks, N. E., Owens, L., and Bird, D. K., Origin of a rhyolite that intruded a geothermal well while drilling at the Krafla volcano, Iceland: Geology, v. 39, no. 3, (2011), p. 231-234.

Farquharson, J., Heap, M. J., Varley, N. R., Baud, P., and Reuschlé, T., Permeability and porosity relationships of edifice-forming andesites: A combined field and laboratory study: Journal of Volcanology and Geothermal Research, v. 297, (2015), p. 52-68.

Grant, M. A., Clearwater, J., Quinão, J., Bixley, P. F., and Le Brun, M., Thermal stimulation of geothermal wells: a review of field data, in Proceedings Proceedings, (2013).

Gudmundsson, A., Infrastructure and Mechanics of Volcanic Systems in Iceland: Journal of Volcanology and Geothermal Research, v. 64, no. 1-2, (1995), p. 1-22.

Heap, M. J., Kennedy, B. M., Pernin, N., Jacquemard, L., Baud, P., Farquharson, J. I., Scheu, B., Lavallée, Y., Gilg, H. A., Letham-Brake, M., Mayer, K., Jolly, A. D., Reuschlé, T., and Dingwell, D. B., Mechanical behaviour and failure modes in the Whakaari (White Island volcano) hydrothermal system, New Zealand: Journal of Volcanology and Geothermal Research, v. 295, no. 0, (2015), p. 26-42.

Kendrick, J. E., Lavallée, Y., Hess, K. U., Heap, M. J., Gaunt, H. E., Meredith, P. G., and Dingwell, D. B., Tracking the permeable porous network during strain-dependent magmatic flow: Journal of Volcanology and Geothermal Research, v. 260, no. 0, (2013), p. 117-126.

Klug, C., and Cashman, K. V., Permeability development in vesiculating magmas: implications for fragmentation: Bulletin of Volcanology, v. 58, (1996), p. 13.

Lamur, A. L., Y.; Wall, R.; Ashworth, J.; Kendrick, J.; Wadsworth, F., Fracture and healing in magmas: a dual role on permeability evolution, EGU General Assembly 2016: Vienna, (2016).

Landsvirkjun, Kröflustod Power Station, Volume 2016, p. http://www.landsvirkjun.com/Company/PowerStations/KraflaPowerStation/ , (2016).

Lavallée, Y., Benson, P., Hess, K.-U., Flaws, A., Schillinger, B., Meredith, P. G., and Dingwell, D. B., Reconstructing magma failure and the permeable degassing network: Geology, v. 41, (2013), p. 515-518.

McClure, M., and Horne, R., An investigation of stimulation mechanisms in Enhanced Geothermal Systems: International Journal of Rock Mechanics & Mining Sciences, v. 72, (2014), p. 18.

Miller, S. A., Modeling enhanced geothermal systems and the essential nature of large-scale changes in permeability at the onset of slip: Geofluids, v. 15, no. 1-2, (2015), p. 338-349.

Mock, J. E., Tester, J. W., and Wright, P. M., Geothermal energy from the earth: its potential impact as an environmentally sustainable resource: Annual review of Energy and the Environment, v. 22, no. 1, (1997), p. 305-356.

Mortensen, A., Egilson, Þ., Gautason, B., Arnadottir, S., and Guðmundsson, Á., Stratigraphy, alteration mineralogy, permeability and temperature conditions of well IDDP-1, Krafla, NE-Iceland: Geothermics, v. 49, (2014), p. 31-41.

Mueller, S., Melnik, O., Spieler, O., Scheu, B., and Dingwell, D. B., Permeability and degassing of dome lavas undergoing rapid decompression: An experimental determination: Bulletin of Volcanology, v. 67, no. 6, (2005), p. 526-538.

Norton, D., and Knapp, R., Transport phenomena in hydrothermal systems; the nature of porosity: American Journal of Science, v. 277, no. 8, (1977), p. 913-936.

Palchik, V., and Hatzor, H. Y., The Influence of Porosity on Tensile and Compressive Strength of Porous Chalks: Rock Mechanics and Rock Engineering, v. 37, no. 4, (2004), p. 331-341.

Paterson, M. S., and Wong, T. F., Experimental Rock Deformation - The Brittle Field, Berlin Heidelberg, Springer, 347 p., (2005),

Saar, M. O., and Manga, M., Permeability-porosity relationship in vesicular basalts: Geophys Res Lett, v. 26, (1999).

Schaefer, L. N., Kendrick, J. E., Lavallée, Y., Oommen, T., and Chigna, G., Geomechanical rock properties of a basaltic volcano: Frontiers in Earth Science, v. 3, (2015).

Schuler, J., Greenfield, T., White, R. S., Roecker, S. W., Brandsdóttir, B., Stock, J. M., Tarasewicz, J., Martens, H. R., and Pugh, D., Seismic imaging of the shallow crust beneath the Krafla central volcano, NE Iceland: Journal of geophysical reserach: Solid Earth, v. 120, (2015), p. 18.

Scott, S., Driesner, T., and Weis, P., Geologic controls on supercritical geothermal resources above magmatic intrusions: Nature Communications, v. 6, (2015).

Siratovich, P. A., Heap, M. J., Villenueve, M. C., Cole, J. W., and Reuschlé, T., Physical property relationships of the Rotokawa Andesite, a significant geothermal reservoir rock in the Taupo Volcanic Zone, New Zealand: Geothermal Energy, v. 2, no. 1, (2014), p. 1-31.

Siratovich, P. A., von Aulock, F. W., Y., L., J.W., C., B.M., K., and M.C., V., Thermoelastic properties of the Rotokawa Andesite: a geothermal reservoir constraint: Journal of Volcanology and Geothermal Research v. 301, (2015).

Stimac, J. A., Powell, T. S., and Golla, G. U., Porosity and permeability of the Tiwi geothermal field, Philippines, based on continuous and spot core measurements: Geothermics, v. 33, (2004).

Violay, M., Gibert, B., Mainprice, D., Evans, B., Dautria, J.-M., Azais, P., and Pezard, P., An experimental study of the brittle-ductile transition of basalt at oceanic crust pressure and temperature conditions: Journal of geophysical reserach, v. 117, (2012).

Walsh, J. B., Effect of pore pressure and confining pressure on fracture permeability: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 18, no. 5, (1981), p. 429-435.

Wong, T.-f., and Baud, P., The brittle-ductile transition in porous rock: A review: Journal of Structural Geology, v. 44, (2012), p. 25-53.

Zang, A., Oye, V., Jousset, P., Deichmann, N., Gritto, R., McGarr, A., Majer, E., and Bruhn, D., Analysis of induced seismicity in geothermal reservoirs–An overview: Geothermics, v. 52, (2014), p. 6-21.

Zierenberg, R. A., Schiffman, P., Barfod, G. H., Lesher, C. E., Marks, N. E., Lowenstern, J. B., Mortensen, A. K., Pope, E. C., Bird, D. K., Reed, M. H., Friðleifsson, G. Ó., and Elders, W. A., Composition and origin of rhyolite melt intersected by drilling in the Krafla geothermal field, Iceland: Contributions to Mineralogy and Petrology, v. 165, no. 2, (2013), p. 327-347.

Zimmermann, G., Tischner, T., Legarth, B., and Huenges, E., Pressure-dependent production efficiency of an enhanced geothermal system (EGS): stimulation results and implications for hydraulic fracture treatments, Rock Physics and Natural Hazards, Springer, (2009), p. 1089-1106.

Acknowledgements

This study has been financed by research funds from Landsvirkjun National Power Company of Iceland as well as a scholarship from the Institute for Risk and Uncertainty at the University of Liverpool and a Starting Grant on Strain Localization in Magma (SLiM, no. 306488) from the European Research Council (ERC).