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Transmissivity of aligned and displaced tensile fractures in granitic rocks during cyclic loading

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ABSTRACT

The pressure dependent fracture permeability of four granitic rock samples was determined in a triaxial test cell under hydrostatic loading conditions at a temperature of 30 °C. Tensile fractures were generated in cylindrical samples by Brazilian tests. Confining pressures were cycled twice between 2 and 50 MPa. Permeability and strain responses were determined for two samples with aligned fracture surfaces and for two samples with a shear displacement of 1 mm. Fracture apertures were also determined optically before and after testing and the fracture surfaces were scanned. Permeability of the intact granite matrix is below $1e-18\ m^2$ and sample permeabilities of fractured samples range between $1e-17\ m^2$ and $1e-12\ m^2$ depending on displacement and confining pressure. Fracture permeabilities of the aligned samples range from $1e-12\ m^2$ to $2e-10\ m^2$ and samples with displaced fracture surfaces have fracture permeabilities between $1e-11\ m^2$ and $2e-9\ m^2$. Without shear displacement, fracture permeability is reduced with time, even at low constant confining pressures of 2 MPa, while fracture permeability is constant at the same conditions for the displaced samples. With increasing confining pressure, permeability reduction is significantly less for the displaced samples compared to the aligned samples. Fracture permeabilities of displaced fractures in granites are similar to fracture permeabilities in sedimentary rocks using proppants. The results indicate that self-propped displaced fractures in granites may allow sufficient fluid flow for reservoir engineering purposes such as enhanced geothermal system development, without the use of propping agents.

1. Introduction

Large amounts of fluids need to be circulated through a hot rock mass for the utilization of geothermal energy. While this is successfully done in conventional geothermal reservoirs, the major potential for geothermal energy development lies in the use of deep and hot, but low permeable, granitic basement rock [1] where fracture networks need to be hydraulically stimulated to achieve economic flow rates. In these enhanced geothermal systems (EGS), fluid flows mainly through natural and induced fractures rather than through the rock matrix. Therefore, the permeability of these fractures is the most crucial parameter governing the hydraulic and thermal performance of an EGS in granitic basement rock. The effective stresses acting on the fracture surfaces depend on the depth and the principal stress magnitudes and directions. In an operating EGS these fractures are also subject to varying pore pressures due to fluid production and injection. That is why knowledge about the pressure dependent permeability of fractures is crucial. Besides the effective stresses acting on the fracture surfaces, fracture permeability is also rock type dependent (e.g. mineralogy and strength) and depends on the fracture properties (e.g. fracture surface roughness).

Pressure dependent fracture permeability of granites has been studied for decades.[2–7] The reported values vary depending on effective closure stress (stress acting on the fracture surface in the direction perpendicular to it,[8] sample size,[9] fracture type,[10] shear displacement,[11] number of pressure cycles,[12] and time.[13] In these tests the fractures were either natural [14] or artificially created by different methods: saw cut,[10] tensile splitting using a wedge,[15] splitting along preexisting veins,[5] (modified) Brazilian tensile testing [6] and shear with different normal loads.[7] The tests were performed with aligned fracture surfaces without shear displacement [6] and shear displacements from as low as 0.07 mm[5] up to 15 mm [11]. Effective closure stresses mostly range between 0 MPa and 50 MPa, but some tests were performed up to

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100 MPa.[6,7] Additionally, fluid flow through fractures was visualized[16] and surface scanning measurements were performed[17] to further characterize this process. Some pressure dependent fracture permeability data are also available from in-situ tests.[18] To the knowledge of the authors, no pressure dependent fracture permeability measurements were performed on fractures in granitic rock using proppants.

Similar experimental schemes were applied to measure fracture permeabilities for oil and gas bearing sedimentary rocks (sandstones, limestones, shales) with proppants[19–21] and without proppants.[19–24] Proppant filled fractures in sedimentary rocks were also tested for geothermal applications.[25]

Major consistent findings from these reported experiments may be summarized as follows: (1) Fracture permeability decreases with increasing effective closure stress. (2) With increasing time, fracture permeability is reduced for all fracture types due to asperity degradation and gouge production (fracture creep). (3) With increasing number of closure stress cycles, fracture permeability is reduced. At least two to three cycles are needed before hysteresis effects become negligible. (4) Saw-cut samples show the lowest permeability values. Aligned natural, tensile, and shear fractures tend to have a slightly higher permeability. It was observed that artificially induced fractures have lower permeabilities than natural fractures. (5) Displaced fractures have a higher permeability than aligned fractures because of the increased aperture due to the mismatch between rough fracture surfaces (self-propping effect). (6) Larger shear displacements lead to higher fracture permeabilities, but after a certain threshold value, the fracture permeability does not further increase with additional shear displacement. (7) Dilation and gouge production are the two factors governing the hydraulic behavior of shear fractures. Shear failure erodes fracture surface asperities. Therefore, a displaced shear fracture has a lower fracture permeability than a manually displaced tensile fracture. This effect increases with increasing normal stress on the fracture plane during shearing. (8) Adding proppants always increases the fracture permeability compared to fractures without proppants (if no significant proppant crushing or chemical effects occur). (9) Findings about the effect of sample size are inconsistent. But in-situ tests show similar permeability values to laboratory tests.

More data are needed to extend and evaluate the significance of these results from earlier studies. The data can then be used to determine the feasibility of an EGS and to set up simple analytical and more complex numerical models to gain deeper insight into the hydro-mechanical behavior of these systems. During the development and operation of an EGS, new fractures might develop and/or existing fractures may open and probably slip due to changes in effective principal stresses during stimulation and injection. Yet, new and existing fractures tend to close again during production in the surrounding of the production wells. In addition to, a stress shadow effect[26] resulting from the opening of fractures may lead to the increase of normal stress on neighboring fractures. Overall, these effects potentially lead to changing effective confining pressures on the fracture surfaces, which may result in fracture opening/closure and permeability increase/reduction.

Since these fractures are the primary flow paths in an EGS it is crucial to know how the stresses in a reservoir change the hydraulic and mechanical fracture apertures and hence their permeabilities. Therefore the objective of this study is to investigate how the permeability of aligned tensile fractures without shear displacement and displaced tensile fractures varies over a wide range of confining pressures and whether aligned and displaced fractures in granites may have permeabilities high enough for economic heat production from an exemplary EGS setting in Northern Alberta.[27]

To test this, five samples were made from four different granitic rocks, which represent this field case. The pressure dependent fracture permeability of the four different granites was determined alongside with the intact sample permeability of one of these granites. In addition to the parameters studied in most of the experiments described above, in this study, the effect of cyclic loading was investigated by performing two confining pressure cycles between 2 MPa and 50 MPa. Also, in this study, the fracture permeability was measured continuously and not only for single effective closure stress levels. Finally, the experimental results were related to the development of enhanced geothermal systems by comparing the laboratory scale experimental results to field scale numerical modeling results from an exemplary EGS reservoir.

2. Sample materials and experimental procedures

Hydraulic and strain response to cyclic changes in hydrostatic confining pressure (2–50 MPa) were measured on five different granitic rock samples. One of the samples was intact, two were fractured with aligned fracture surfaces, and two were fractured with displaced fracture surfaces (Fig. 1). Additionally, the time dependent permeability and strain behavior at a constant confining pressure of 2 and 50 MPa was determined over the course of several hours. In this section the tested rock samples and the experimental procedures are described.

2.1. Sample materials

Five samples were prepared from four different granitic rocks. Three of these rocks are granodiorites from outcrops in the Annabel Lake shear zone in Saskatchewan, Canada.[28] These are considered representative for the modeled EGS site in Northern Alberta. Additionally, a Sierra Granite from a quarry in California was tested as a well-known standard material. Out of the granodiorites two samples were tested with displaced fracture faces having the same displacement of 1 mm and one sample was tested with aligned fracture faces. For comparison also an intact granodiorite and an aligned Sierra Granite were tested. An overview of some properties of the tested rocks is given in Table 1. Note that the strengths of the samples are slightly different and the rock matrix is almost impermeable with a very low porosity (e.g. 0.9% for the Sierra Granite sample[29]). The samples were all cylinders of 10 cm length and 5 cm diameter.

2.2. Fracture generation

Tensile fractures were induced at the center of the intact samples along the axial sample direction by Brazilian tensile testing.[30] The tests were performed with a constant displacement of 0.0003 mm/s. The slow displacement rate was beneficial for the development of a single defined fracture and to avoid sample disturbances such as fracture branching. During fracture generation the samples were kept in a heat-shrinkable tube to keep the two halves of fractured sample together, avoid breakouts and ease transportation. After fracture generation the heat-shrinkable tube was removed. Without the tube the fracture surfaces of the Sierra Granite Sample remained stuck together whereas, for all other samples, both sample halves were completely separated. Thus, the Sierra Granite sample had a significantly smaller initial fracture aperture compared to the others. Since the force was measured during Brazilian tensile testing, the Brazilian tensile strength of all rocks was calculated as an indication for the strength of the samples (Table 1).