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Hydraulic fracturing under high temperature and pressure conditions with micro CT applications: Geothermal energy from hot dry rocks

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ABSTRACT

Hydraulic fracturing has been widely employed to enhance the permeability of tight geological formations including deep geothermal reservoirs. However, due to the complex in-situ stresses, high-temperature conditions and heterogeneity of the formations, hydraulic fracturing under deep geothermal conditions is poorly understood to date. The aim of the current study is, therefore, to investigate the effect of reservoir depth, temperature, and sample heterogeneity during hydraulic fracturing and the influences of rock micro-structure on fracture propagation. A series of hydraulic fracturing experiments was conducted on two Australian granite types under a wide range of confining pressures from 0 to 60 MPa and temperatures from room temperature to 300 °C simulating different geothermal environments. The corresponding micro-structural effects on the rock matrix were investigated employing high-resolution CT imaging using the IMBL facility of the Australian Synchrotron. According to the results, the breakdown pressure of reservoir rock linearly increases with reservoir depth (confining pressure). However, with increasing temperature breakdown pressure linearly decreases. This corresponds to the linear reduction of tensile strength measured by high-temperature Brazilian tensile tests. In addition, CT images showed that the injection of cold water into hot rock can result in a porous zone with porosity ranging from 2 to 3% close to the wellbore due to thermally-induced inter- and intra-crystalline cracks. In this condition, fluid leak-off is high and the measured fracture aperture of the main hydraulic fracture is relatively small. Further, fracture propagation paths and apertures are mainly controlled by the stress state and the heterogeneity of the rock matrix. It was found that fractures tend to propagate along preferential paths, mainly along grain boundaries and in large quartz and biotite minerals (grain size > 0.3 mm) and minerals with pre-existing micro-cracks.

1. Introduction

The exploration of new energy resources is essential to fulfill the energy demands of the increasing population. In this regard, apart from conventional geothermal resources, a new field of geothermal systems known as enhanced or engineered geothermal systems (EGSs) has been proposed, utilizing geothermal resources located deep underground [1]. These systems are associated with deep geological formations at depths of around 1–4 km with high-temperature rock formations (temperatures around 100–300 °C), particularly those with ultra-low permeability characteristics [2]. Therefore, permeability enhancement techniques play a critical role in the reservoir stimulation of these systems.

Favourable conditions for EGS are pre-existing, critically stressed and optimally oriented fractures. It is essential to create a number of interconnected fractures to enhance the thermodynamic efficiency and production of the reservoir [1,3]. In order to stimulate the reservoir, hydraulic fracturing, which is widely employed to enhance the productivity of unconventional wells, is generally applied in EGS. In the current technology, pressurized fluid is injected through the wellbore

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(injection well) to create the desired fracture volume. This enables the creation of a proper hydraulic connection between the injection and production wells and then the heated fluid can be extracted to the surface through one or more production wells to operate steam turbines for electricity generation.

However, due to the complex stress conditions, the presence of pre-existing fractures, fluid loss, the transport of proppant and temperature effects, the prediction of hydraulic fracturing process parameters (injection flow rate and stages of fracturing), breakdown pressure (the pressure at which the rock is fractured), and the size and extensiveness of hydraulically- induced fractures is challenging in the EGS environment. A number of studies have identified the parameters governing hydraulic fracturing, including reservoir properties (stress state, temperature, mechanical characteristics, and mineralogy) and injection fluid properties (flow rate, viscosity, and compressibility) [4–8]. Laboratory-scale hydraulic fracturing experiments have provided valuable information on the hydraulic fracturing process compared with the complexities associated with field-scale exercises.

In their experimental work, Zoback et al. [6] found that hydraulic fractures always propagate along the major principal stress. Further, the difference of horizontal stresses determines the breakdown pressure, shape, quantity and propagation of fractures (i.e. either single or multiple fractures) [4]. In the presence of pre-existing fractures, hydraulic fracture propagation is certainly altered, and the angle of approach and the shear strength of the pre-fracture are important aspects in this regard [9,10]. According to Warpinski and Teufel [8], hydraulic fractures are capable of extending across natural fractures, depending on the stress state and the location of the pre-existing fracture. For example, according to Blanton [11] and Warpinski and Teufel [8], hydraulic fractures can cross pre-existing fractures only under higher differential stresses, or else they are deviated by the natural fractures. In addition, the presence of notches has an influence on breakdown pressure due to the stress concentration, and Fallahzadeh et al. [12] identified a reduction of breakdown pressure with notches. Further, the length of notches also has an influence on breakdown pressure, such that the longer the notch length, the smaller the breakdown pressure [5]. The injection rate also has an evident relationship with breakdown pressure, since higher injection rates can result in faster fracture propagation [6]. It has also been identified that the viscosity of the injection fluid influences the fracture morphology, such that low viscose fluid (i.e. air, foam, CO_2) can result in complex multiple fractures [13,14].

In relation to laboratory-scale hydraulic fracturing experiments, only a limited number of studies have employed real rocks, and most of the work has been done with artificial materials including concrete, cement mortar and Perspex [5,15]. In terms of their material properties (brittleness, cohesion, friction, porosity, permeability etc.), it is questionable whether these studies are applicable to real rock applications. Further, due to the limitations of appropriate instrumentation, many experiments have been conducted under small pressure conditions [16,17] and none of the experiments has been performed under the extreme pressure and temperate conditions employed in the present study (confining pressure up to 60 MPa and temperature up to 300 °C) to date. Therefore, a significant knowledge gap exists in terms of hydraulic fracturing experiments conducted on real rock specimens under in-situ stress and temperature conditions. In addition, hydraulic fracturing experiments are generally designed with large rock blocks (mostly cubic specimens of 30–1000 mm) and few studies have paid attention to rock micro-structural influences during hydraulic fracturing [18–20]. Therefore, understanding of the effect of the heterogeneous nature of the rock during hydraulic fracturing under stress and temperature conditions is insufficient to date. With high-resolution CT scanning technology, the present study captured the coupled in-situ stress and temperature effects at both micro- and *meso*-scale and these combined experimental studies provide knowledge of the underlying mechanisms of geothermal reservoir rocks in terms of fracture geometry, fracture propagation, and thermally-induced damage. Therefore,

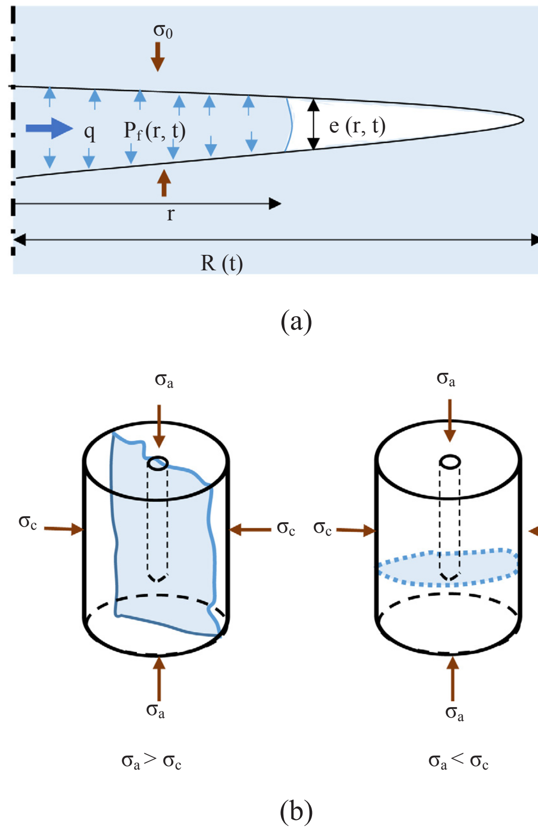

Fig. 1. (a) Hydraulic fracture propagation in an elastic rock mass, (b) Hydraulic fracture patterns due to different stress conditions.

it is expected that the present work will be beneficial for the geothermal industry, where poro-thermo-mechanical effects play a crucial role.

2. Theoretical background

Theoretical work on hydraulic fracturing has concerned three main processes and different theories have been employed for these conditions: (1) the deformation of the fracture surface is often considered employing linear elasticity; (2) fracture propagation is often associated with linear elasticity and fracture mechanics theory with fluid flow equations to calculate the leak-off effects (3) the fluid flow of the fracture is discussed using the power law [21,22]. In the theoretical work on fracture propagation, a number of approaches have been proposed for more than half a century. Among them, the Kristianovic-Green-de Klerk (KGD) model [23] and the PKN model [24] can be identified as the two major approaches employed in classic hydraulic fracturing 2-D models. Considering planar KGD, radial axisymmetric geometry and the hydraulic fracture which propagates in an impermeable rock due to the injection of incompressible Newtonian fluid at a constant volumetric flow rate, the penny-shaped model (Fig. 1(a)) has been considered by many authors [25–27]. The solution to this problem can be found in Perkins and Kern [28] and Bunger et al. [25] with a number of associated complexities, including secondary crack effects [27], and rock strata and thermal and poro-elastic effects [29].

In hydraulic fracturing the in-situ stress state has been identified as the factor dominating the morphology of induced fractures [30]. Once the axial/vertical stress is larger than the confining stress, fractures initiate along the wellbore (vertical plane), and when the axial stress is less than the confining stress, fractures initiate across the wellbore (horizontal stress), as illustrated in Fig. 1(b). In the present study, it was ensured that the vertical stress was higher than the confining pressure, and the fracture always propagated along the well-bore. Therefore, in