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Pressure analysis of the hydromechanical fracture behaviour in stimulated tight sedimentary geothermal reservoirs

Stefan Wessling[a,*], Ralf Junker[a], Jonny Rutqvist[b], Dmitriy Silin[b], Hans Sulzbacher[a], Torsten Tischner[c], Chin-Fu Tsang[b]

[a] *Leibniz Institute for Applied Geosciences, Stilleweg 2, D-30655 Hannover, Germany*
[b] *Lawrence Berkeley National Laboratory, Earth Sciences Division, MS 90-1116, Berkeley, CA 94720, USA*
[c] *Federal Institute for Geosciences and Natural Resources, Stilleweg 2, D-30655 Hannover, Germany*

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ABSTRACT

Hydromechanical phenomena in fractured sediments are complex. They control the flow in stimulated tight sediments and are crucial for the exploitation of geothermal energy from such rocks. We present the analysis of a cyclic water injection/production (huff–puff) process, a promising method to extract geothermal energy from tight sedimentary reservoirs. It uses a single borehole, which considerably reduces investment costs. A huff–puff test was performed in a 3800-m deep sedimentary formation (borehole Horstberg Z1, Lower Saxony, Germany). The analysis presented herein explains the downhole pressure measurements by a simplified reservoir model containing a single vertical fracture. The model addresses the flow behaviour between the fracture and the rock matrix in a layered formation, and the coupling between fluid flow and the mechanical deformation of the fracture. The latter aspect is relevant to predict the efficiency of the geothermal reservoir because cooled regions resulting from a particular injection/production scheme can be identified. The analysis methods include: (1) the curve-fitting code ODA used for a determination of different flow regimes (radial or linear), (2) an analytical solution for the calculation of the injection pressure, assuming a time-dependent fracture area, and (3) the simulator ROCMAS, which numerically solves the coupling between fluid flow and fracture deformation. Whereas each single approach is insufficient to explain the complete test data, a combination of the results yields an understanding of the flow regimes taking place during the test.
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1. Introduction

Since the commercial viability of an Enhanced Geothermal System not only depends on high fluid production temperatures but also on high flow rates, reservoir stimulation is frequently used to increase well productivity (Murphy et al., 1999; Wallroth et al., 1999; Megél et al., 2006). In the case of hydraulic stimulation by massive fluid injection, coupled hydraulic and mechanical reservoir processes are involved. In particular, the coupled effect of mechanical fracture opening (causing rock deformation) resulting from increased fluid pressure in the fracture is important because fractures tend to be the main fluid flow pathways in tight (low-permeability) rock masses. Such hydromechanical effects were previously investigated numerically by Min et al. (2004), who determined the change in effective permeability of a fracture network for different loading conditions.

In recent years, some geothermal projects have been initiated to investigate the extraction of geothermal energy (i.e. heat) stored in tight sedimentary formations (see for example Orzol et al., 2004; Tischner et al., 2004; Legarth et al., 2005; MIT, 2006). After hydraulic stimulation, the systems hosted in sedimentary rocks are frequently described by simplified models that include a single (man-made) fracture.

Strongly coupled hydraulic and mechanical processes are described in the hydraulic fracturing context, in which the fluid pressure-induced opening of fractures increases the stress at the fracture tip until rock failure occurs and the fracture propagates; see Valko and Economides (1997) for a detailed overview. However, hydraulic fracturing theories and related approaches deal with the pressure regime where fractures propagate by tensile failure, which is above the minimum principal stress (also referred to as the closure pressure). Under this regime, the fluid pressure-induced fracture deformation depends on the mechanical properties (Young's modulus, Poisson ratio) of the bounding rock; hence, the fracture stiffness (a nonlinearly changing aperture below the closure pressure) is not considered. The change in fracture properties with respect to fluid pressure or loading variations has been

* Corresponding author at: Baker Hughes INTEQ GmbH, Baker-Hughes-Strasse 1, D-29221 Celle, Germany.
E-mail address: stefan.wessling@inteq.com (S. Wessling).

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Nomenclature

A	fracture area (m^2)
b	fracture aperture (m)
C	bulk modulus (Pa)
$\mathbf{D}$	mechanics coefficients tensor (Pa)
D_h	hydraulic diffusivity (m^2/s)
E	Young's modulus (Pa)
$\mathbf{F}$	body force vector per unit volume (N/m^3)
F	factor (Eq. (1)) ($Pa\sqrt{s}/m^3$)
H	aquifer thickness (m)
$\mathbf{I}$	identity tensor
k	permeability (m^2)
K	stiffness (Pa/m)
M	Biot's modulus (Pa)
p	pressure (Pa)
Q	flow rate (injection or production) (m^3/s)
q	specific fluid source (1/s)
r	fracture radius (m)
S	storativity (m/Pa)
Sk	skin
t	time (s)
T	transmissivity ($m^3/(Pa\,s)$)
$\mathbf{u}$	displacement vector (m)
x_f	fracture half length (m)
X	factor (Eq. (9)) ($1/\sqrt{s}\,m^3$)

Greek symbols

α	Biot–Willis coefficient
β	pre-exponential factor (1/s)
γ	fracture area growth exponent
$\boldsymbol{\varepsilon}$	strain vector
ε_V	volumetric strain
μ	fluid viscosity (Pa s)
ν	Poisson's ratio
σ_n	total stress normal to the fracture plane (Pa)
σ'_n	effective stress normal to the fracture plane (Pa)
Φ	porosity

Subscripts

f	fracture
fl	fluid
g	grain
hist	history
i	injection
l	linear
m	matrix
n	normal
0	initial
r	radial
res	residual
s	at shut-in start
t	tangential

Conversion

L/s	$1\,L/s = 10^{-3}\,m^3/s$

investigated by a number of authors. For example, experiments have been performed to understand the interrelation between changes in fluid flow rates or fracture apertures and loading conditions (Olsson and Brown, 1993; Yeo et al., 1998; Sausse, 2002). Numerical investigations designed to understand the influence of normal and shear closure on fracture aperture were performed by Matsuki et al. (2006) and Ghassemi and Kumar (2007).

Whereas the investigations cited above aim to understand the hydromechanically controlled fracture opening and/or closure by way of laboratory experiments or numerical simulation, little effort has been made to interpret hydraulic test data with respect to the fluid pressure-induced changes in fracture aperture. Thus, the influence of mechanically opening fractures on the fluid pressure response has rarely been described. Also, conventional pressure-transient analysis is restricted to relatively small volume, short-duration fluid injection operations followed by lengthy pressure falloff periods (Legarth et al., 2005; Craig, 2006). One possibility to investigate the fracture deformation with respect to fluid pressure changes is to perform pressure-step tests (jacking tests), as described in Singh et al. (1987), Rutqvist et al. (1992) and Lizak et al. (2006). In this case, the hydraulic aperture of fractures starts changing in a non-linear fashion while the injection pressure remains below the compressive stress across the fracture. Rutqvist (1995) presents the determination of fracture normal stiffness by a combination of in situ pulse and jacking tests and numerical simulations, and defines a stress-permeability relation for fractures.

Here we analyze a huff–puff test (cyclic fluid injection/extraction) involving hydromechanically behaving fractures. By this behaviour we mean that the change in fluid pressure in the fractures affects the effective stress and thus causes mechanical fracture deformation (opening or closure), which in turn leads to a change in the hydraulic aperture and consequently influences fluid pressures. The test was performed in a geothermal sedimentary reservoir at 3800 m depth that had previously been stimulated by massive water injection. The analysis shows that only the consideration of such a hydromechanical fracture behaviour can explain the downhole pressure (build-up and decay) history that was recorded during the huff–puff test.

We will not deal with fracture propagation mechanisms because, for most parts of the test, the pressure is below fracture propagation level. Instead, we assume that fractures (artificially created by hydraulic stimulation) already exist in the reservoir at the time when the test began. Furthermore, we simplify our analysis by considering a model that only includes a single fracture. Of course, the more likely case that multiple fractures may actually exist is not addressed here, but the simplified model is adequate to explain the recorded downhole pressure changes. The analysis concentrates on the hydromechanical behaviour of the single fracture, which has been simulated with ROCMAS (Noorishad et al., 1992; Rutqvist et al., 1998); poroelastic effects in the bounding rock matrix are not investigated by the simulation.

In our study, we applied three different methods, which allow for varying degrees of complexity. The computer code 'Operation Data Analysis' (ODA) developed by Silin and Tsang (2002) was used to analyze the pressure behaviour in the traditional way, i.e. estimating hydraulic reservoir properties by curve fitting the measured pressure data against analytical solutions for radial and linear flow. The code is based on the conventional transient fluid flow model, but incorporates pre-test pressure distribution near the wellbore. An alternative analysis of hydromechanical effects was performed by curve fitting an analytical solution for the injection pressure that includes a time-dependent growth of fracture area (Silin and Patzek, 2001). This method can determine whether a changing fracture area would be an explanation for the observed pressure transients, but the resulting area proved to be unrealistically high.

Instead, a change in the fracture volume (due to the fracture opening at injection) is a more reasonable explanation, as shown by a numerical simulation of fracture–matrix flow, whereby the fracture aperture becomes a function of the coupling between the rock deformation and the fluid pressure in the fracture. We use the finite-element code ROCMAS in our simulations. The analysis demonstrates that a combination of different approaches is useful and necessary to understand the processes involved throughout

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