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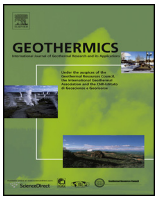

The influence of thermal-hydraulic-mechanical- and chemical effects on the evolution of permeability, seismicity and heat production in geothermal reservoirs

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ABSTRACT

A coupled continuum model representing thermo-hydro-mechanical behaviors is applied to follow the evolution of induced seismicity within a prototypical enhanced geothermal system (EGS) reservoir. The model is applied to the potential Newberry EGS field (USA) by assuming fracture sizes of 10–1200 m. Models are classified by their conceptualization of the fractured reservoir geometry as networks of discrete fractures and with equivalent fractured media as fill-in. The THMC model is applied to a doublet injector-producer to explore the spatial and temporal triggering of seismicity for varied fracture network geometries both shallow (2000 m) and at depth (2750 m). The magnitude of the resulting seismic events is in the range −2 to +1.9. The largest event size (∼1.9) corresponds to the largest fracture size (∼1200 m) within the reservoir. The rate of hydraulic and thermal transport has a considerable influence on the amount, location, and timing of failure, and ultimately, on the event rate. The event rate is highest when the fracture density is highest (0.9 m^{-1}) and the initial stresses highest (at depth). In all cases, the *a*-value decreases and the *b*-value increases with time. The *b*-value is largest (∼1.34) for the highest fracture density and the highest stress regime. Thermal energy recovered during production is also greatest at depth and for the highest density of fractures.

1. Introduction

In enhanced geothermal systems (EGS), fluid circulation is influenced by thermal-hydro-mechanical effects in the short-term and by chemical reactions in the long-term. These effects may alter fluid transport properties and as a result enhance the permeability of fracture networks (Elsworth, 1989; Goodman, 1976a; Polak et al., 2003; Renshaw, 1995). Natural and induced fractures, as well as the geometry of fracture networks, have an important influence on both the evolution of permeability (Polak et al., 2003; Yeo et al., 1998) and on induced seismicity (Shapiro and Dinske, 2007).

Many field experiments (Audigane et al., 2002; Delépine et al., 2004; Jung et al., 1996; Rutledge and Phillips, 2003; Zoback and Harjes, 1997) and models (Rutqvist et al., 2001; Shapiro et al., 1998, 2002; Taron et al., 2009a) have been used to determine the key factors influencing the principal processes of permeability enhancement and how they will influence induced seismicity by the action of hydraulic or thermal effects at different times (Baisch, 2009; Deichmann and Giardini, 2009; Dinske et al., 2010; Evans et al., 2005; Shapiro and Dinske, 2007; Taron and Elsworth, 2009; Taron et al., 2009a,b; Yasuhara et al., 2004). Simulating these behaviors requires that the linkage between the fluid and thermal behaviors and the role of fracture networks be defined within the reservoir. This work attempts to determine- how such processes will evolve through time.

Circulating fluid at elevated pressures within naturally fractured reservoirs may cause induced seismicity in the early stages of reservoir stimulation (few weeks) (Rothert and Shapiro, 2003; Rutledge and Phillips, 2003; Shapiro et al., 2002). Hydraulic effects observed during the stimulation of EGS reservoirs influence the permeability and dilation of existing fractures by altering the direction and magnitude of the reservoir stress field. Circulating fluid-induced thermal stresses may also enhance reservoir permeability by creating new fractures and by enhancing the permeability of existing fractures. Both of these effects may induce seismicity both during stimulation and later long-term production.

In this work, we apply a THMC flow-transport-deformation simulator to examine the importance of these factors on reservoir evolution and specifically on the strength of their influence. The focus of this study is to observe the evolution of dominant

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fracture behaviors that lead to enhanced permeability and induced seismicity during the long-term (~20 year) production of thermal energy from engineered geothermal systems (EGS). We also focus on the significant influence of fracture density and fracture spacing on long-term reservoir behavior.

This paper provides a brief description of the fracture network model and mechanisms of shear failure that result from circulating cold injection fluids at modest overpressures and under pressures. Effective stresses, modulated by fluid pressures and thermal stresses, are used to define the spatial and temporal release of seismic energy as individual fractures are reactivated in shear. The progress of fluid pressures and cooling in the reservoir is represented by the advancement of the hydrodynamic and thermal fronts as well as the progress of pore-pressures and thermal stresses within the reservoir. The triggering of seismicity and the frequency–magnitude distribution (*a*- and *b*-values) of this seismicity is indexed to the progress of these fluid and thermal fronts. These behaviors are evaluated for parameters that broadly represent the planned Newberry Volcano EGS demonstration project and follow the anticipated evolution of the seismic event-size distribution due to fluid and thermal effects during long-term stimulation. Finally, and perhaps most importantly, the relative effects of the above mechanisms on the ultimate recovery of thermal energy from the EGS reservoir are evaluated.

2. Reservoir simulation

The simulations presented in the following uses a THMC simulator (Taron and Elsworth, 2009) that couples the multiphase, multicomponent, non-isothermal thermodynamic, reactive transport and chemical precipitation/dissolution capabilities of TOUGHREACT with the stress/deformation analysis by using the numerical modeling code FLAC^{3D}. The model incorporates the effects of fractured reservoirs involving fracture networks of variable densities and connectivities while considering various reservoir conditions, including initial stress, temperature, and permeability – as these may exert significant influence on the evolution of permeability and seismicity.

Brittle failure on pre-existing fractures is represented as a prescribed stress drop (~3 MPa). For a prescribed frictional strength, the model calculates the shear resistance from the change of normal stress and pore pressure. Stress builds and reaches a peak strength, which then rapidly declines to a residual strength (Goodman, 1976b; Jaeger et al., 2007). This model is used to follow the evolution of seismic rupture within the system.

The principal assumption in this procedure is that strength will fully recover in the interseismic period, allowing the failure cycle to repeat once shear stresses have rebuilt. To define the evolution of failure in a stimulated reservoir, the failure of the seeded fractures is calculated within FLAC^{3D}. Strength is determined by comparing the peak strength and residual shear strength, according to the Mohr–Columb criterion (see Table 2).

2.1. Characteristics of the reservoir

This model is now applied to a doublet geometry within a reservoir with half-symmetry (2000 m × 1000 m × 300 m; Fig. 1), representing the Newberry geothermal field. The Newberry demonstration EGS project is located southeast of Bend, Oregon. Data from well NWG 55–29 are used to build the reservoir model used in the subsequent simulation (Cladouhos et al., 2011). This presumed half-symmetry is approximate but represents the essence of important behaviors that act in the reservoir. A single well injects water at a constant temperature with a withdrawal well separated by 700 m. Boundary stresses, in both horizontal and vertical directions, as well as pore pressure and temperature roughly corresponding to depths of 2000 and 2750 are applied to two different realizations of the geometry (Table 2) applied for this geothermal field. The characteristics and the values of the parameters in the simulation for the in situ reservoir are defined in Table 1.

Table 1
Solid medium properties as used in simulations.

Parameter	Unit	Newberry
Bulk modulus of intact rock(K_m)	GPa	17
Cohesion	MPA	10
Poisson's ratio(υ)	–	0.27
Bulk modulus of fluid(k_f)	GPa	8
Bulk modulus of solid grain(K_s)	GPa	54.5
Internal friction angle(φ)	°	35
Residual friction angel(ß)	°	11
Coefficient of thermal expansion(α_T)	1/°C	1.2E−5
Thermal conductivity(λ)	W/m K	2.9
Heat capacity(c_p)	J/kg K	918
Initial permeability (k)	m^2	1.10E−17
Porosity within fractures (ϕ)	–	0.3

Table 2
Parameters utilized in the simulation.

Parameters	Unit	Depth (m)	
		2000 Zone B	2750 Zone D
S_{hmin}	MPa	36	50
SH_{max}	MPa	48	64
S_v	MPa	48	66
$P_{injection}$	MPa	29	35
$P_{reservoir}$	MPa	24	30
$P_{production}$	MPa	19	25
Peak strength	MPa	25	35
$T_{reservoir}$	°C	230	290
$T_{injection}$	°C	20	20
Specific heat	kJ/kg K	4.65	5.6

Prior to long-term production, the reservoir is hydraulically stimulated by elevating fluid pressures and quenching the reservoir at the injection well and withdrawal well over a period of 21 days and at an overpressure of 5 MPa (Izadi and Elsworth, 2014). This dilates pre-existing fractures (fracture propagation is not considered) and allows the development of hydroshears. During the short stimulation (~21 days), four zones – at depths 2000, 2500, 2750 and 3000 m – are considered for reservoir stimulation (Izadi and Elsworth, 2014).

During this stimulation a similar evolution of permeability and progress of seismicity is observed for both zones B (shallowest, located at 2000 m depth) and E (deepest, located at 3000 m depth), and for both intermediate zones C and D (due to the similar form of the fracture networks (0.9 m^{-1}) in zones C and D). Thus, in this study, numerical experiments are conducted for the shallow zone B (with 0.5 m^{-1} fracture density) and deep zone D (with 0.9 m^{-1} fracture density), alone, as representative of the reservoir. These represent behavior at two different depths of 2000 m and 2750 m to examine the roles of the critical influencing parameters, viz. fracture geometry and stress. Each of these zones requires different inputs for fracture orientations, density and spacing (Table 3). Available, but sparse, fracture data for the Newberry geothermal field (Cladouhos et al., 2011) are used to build the fracture networks for the models. Following stimulation, cold fluid (20 °C) is circulated within the reservoir in the doublet pattern of Fig. 1. The resulting analyses examine the progress of seismicity for long-term production as the reservoir is developed in terms of rates, magnitudes and locations.