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Reservoir permeability mapping using microearthquake data

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ABSTRACT

Evaluating hydraulic properties of fractured reservoirs both during and after stimulation is vital for the development of Enhanced Geothermal System (EGS). To constrain the evolution of fracture permeability at sufficiently fine resolution to define reservoir response, we propose a model that couples the moment magnitude to fracture aperture and then estimates the reservoir permeability at relatively high resolution. The critical parameters controlling fracture aperture and permeability evolution are stress-drop, the bulk modulus of the fracture embedded matrix, and the dilation angle of fractures. We employ Oda's crack tensor theory and a cubic-law based analog to estimate the permeability of a synthetic fractured reservoir at various scales, demonstrating that the resolution of permeability is largely determined by the cellular grid size. These methods are applied to map the in-situ permeability of the Newberry EGS reservoir using observed microearthquakes (MEQs) induced during two rounds of reservoir stimulations in 2014. The equivalent mean permeability evaluated by each method is consistent and unlimited by representative elementary volume (REV) size. With identical parameters, Oda's crack tensor theory produces a more accurate estimation of permeability than that of the cubic law method, but estimates are within one order of magnitude. The permeability maps show that the most permeable zone is located within the zone of most dense seismicity, providing a reference for the siting of the production well. This model has the potential for mapping permeability evolution from MEQ data in conventional and unconventional resources and at various scales.

1. Introduction

Some unconventional resources, such as geothermal energy, have the potential to enable a transition to a more sustainable energy future. Enhanced Geothermal Systems (EGS) have the potential to tap the Earth's vast thermal resource. Since fractures are the most abundant structural feature in the upper crust (Warren and Root, 1963) and a fracture surface may have much higher permeability than the surrounding rock matrix and therefore operate as a conduit for fluids, a key capability for the successful development of EGS is to generate sufficient permeability in naturally fractured reservoirs via hydroshearing and to optimally accommodate the production well according to the identified locations of clustered fractures (Rinaldi et al., 2015; Cladouhos et al., 2016). Traditionally, information on fracture attributes has come from well data (Barthélémy et al., 2009; Zeeb et al., 2013), but for reservoirs undergoing active stimulation at a greater depth, microseismic monitoring is the most effective and useful method to characterize the spatial distributions of fractures as well as fluid migration in the subsurface (Maxwell and Urbancic, 2001; Maxwell et al., 2010; Downie et al., 2013). This reservoir feedback occurs since the injected fluid reactivates pre-existing fractures and thus triggers microearthquakes (MEQs) (Nicholson and Wesson, 1990; Majer et al., 2007; Suckale, 2009; Ellsworth, 2013; Guglielmi et al., 2015). Hence it is of particular interest to evaluate the properties of fractures and to estimate the evolution of permeability – it has become essential and necessary to establish a model that accurately captures the hydraulic properties using the crucial feedback on stimulation contained within the observed MEQs.

A number of previous studies have provided insight into connections between in-situ MEQ data, inferred subsurface fluid migration and reservoir state. For example, the hydraulic diffusivity may be defined from the analysis of the spatio-temporal growth of the fluid-injection-induced seismic cloud (Shapiro et al., 1997, 2006). If the leading edge of the seismic cloud is presumed coincident with the fluid pressure front, then fluid diffusivity may be evaluated at reservoir scale (Hummel and Shapiro, 2012). However, this method ignores local geomechanical effects and variations in fracture permeability caused by hydroshearing. As a result, it cannot constrain permeability at finer

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Nomenclature

a^*	Frictional parameter (direct effect)
A	Area of the fracture surface
b	b-value
b^*	Frictional parameter (evolution effect)
b_f	Fracture aperture
b_m	Mechanical aperture at low reference stress
b_n	Normal aperture
b_{nIni}	Normal aperture before fluid injection
b_{nFin}	Normal aperture after fluid injection
b_r	Residual aperture
b_s	Shear aperture
c_n	Contribution coefficient of tensile failure
c_s	Contribution coefficient of shear failure
D_p	Reservoir depth
e	Power-law scaling exponent
E	Young's modulus
F_{ij}	Fabric tensor
G	Average shear modulus of fracture embedded rock mass
k_{ij}	Permeability tensor
k_m	Mean permeability
k_{matrix}	Matrix permeability
k_T	Source-type parameter
k_{tot}	Total mean permeability
k_{aseis}	Mean permeability of aseismic fracture networks
k_{seis}	Mean permeability of seismic fracture networks
K	Bulk modulus
K_{IC}	Stress intensity factor
K_s	Fracture stiffness
l	Fracture trace length
l_h	Fracture radius or half length
L_{rev}	Scan line or imaginary grid size (REV size)
M	Moment tensor
M_0	Seismic moment
M_0^s	Seismic moment for pure shear failure
M_0^n	Seismic moment for pure tensile failure
M_w	Moment magnitude
n	Number of fracture
$\mathbf{n}$	Unit vector of the fracture plane
N_{tot}	Total population of fractures
N_{aseis}	Population of aseismic fractures with size less than critical length
N_{seis}	Population of seismic fractures
N_f	Number of activated fractures
N_{uf}	Number of unactivated fractures
P_0	Initial hydrostatic pore pressure
P_f	Total fluid pressure
P_f^{crt}	Critical fluid pressure at which the pre-existing fracture is reactivated
P_w	Wellhead pressure
P_{wf}	Minimum wellhead pressure required to reactivate pre-existing fractures
$\bar{S}$	Average fracture spacing
S_{aseis}	Spacing of aseismic fractures
S_{seis}	Spacing of seismic fractures
S_f	Fracture spacing
S_H	Maximum horizontal stress
S_h	Minimum horizontal stress
S_v	Vertical stress
S_1	Maximum principal stress
S_3	Minimum principal stress
Δu_{max}	Maximum final dislocation for 100% stress drop
Δu_n	Average normal opening
Δu_s	Average shear displacement
V_{rev}	Representative elementary volume
V_0	Reference velocity
V_f	Coseismic velocity
α_f	Pre-factor of aperture-to-length scaling law
α_s	Stiffness parameter
ρ_{frac}	Density of centers of fracture planes
ρ_c	Density constant in fracture length-frequency power law
δ_{ij}	Kronecker delta
η	Fracture geometric factor
θ	Fracture orientation
λ	Nondimensional coefficient
μ_s	Static friction coefficient
$\Delta\mu$	Frictional drop
ν	Poisson's ratio
ξ	Exponent in the fracture length-frequency power law
σ_n	Normal stress
σ_n^{crt}	Critical normal stress at which the pre-existing fracture is reactivated
τ	Shear stress
$\Delta\tau$	Stress drop
$d\Omega$	Solid angle
ψ	Dilation angle

resolution. In addition, a viable approach estimates a linkage between triggering fluid pressures and in-situ MEQ data (Terakawa et al., 2010, 2012). This method integrates focal mechanism tomographic techniques and the Mohr-Coulomb failure criterion to indicate the fluid pressure along the fracture plane at the time of slip. Though this work provides constraint of a 3D distribution of fluid pressures in the stimulated zone of the reservoir, it does not include the contribution of the fracture network to the evolution of hydraulic properties (*i.e.,* permeability heterogeneity) that are of principal interest for long-term EGS production. Meanwhile, Ishibashi et al. (2016) have tried to link the microseismicity to the permeability evolution by considering the topography of fracture/fault surfaces.

In the following, we propose a model to couple in-situ MEQ data and in-situ permeability at various reservoir scales. This model assumes that induced seismicity is controlled by the Mohr-Coulomb failure criterion and applies the moment magnitude of MEQs to recover fracture shear slip (Stein and Wysession, 2009). We explore two alternate approaches – (1) the cubic law based equivalent porous-medium method (EPM) and (2) Oda's crack tensor theory (*i.e.*, discrete fracture network (DFN)) to approximately define the permeability at a suitable representative elementary volume of the reservoir (REV).

The cubic law may be used to link permeability of the reservoir to the aperture of fractures, as a fundamental parameter that, in turn, may be indexed to seismicity. As fluid is usually channeled in permeable fractures that occupy only a small volume of the rock mass, it is important to characterize such hydraulic properties with consideration of the appropriate length scale. The hydraulic properties of the fracture network are captured as an equivalent permeability (Snow, 1969; Tsang and Witherspoon, 1981) for parallel or ubiquitous joints. An alternate approach is to use a discrete fracture model (Oda, 1982) in the evaluation of permeability. Thus a model-fabric tensor may be used to describe the geometric characteristics of fractured rock and to determine transport characteristics (Oda, 1982, 1984).

In this study, we are primarily interested in the sensitivity of parameters that control stress state and fracture properties, and their significance in influencing the moment magnitude of MEQs and the evolution of permeability before and after seismic slip. We use a synthetic model to explore the features of the two methods and indicate the

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