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Maximum magnitude of injection-induced earthquakes: A criterion to assess the influence of pressure migration along faults

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ABSTRACT

The maximum expected earthquake magnitude is an important parameter in seismic hazard and risk analysis because of its strong influence on ground motion. In the context of injection-induced seismicity, the processes that control how large an earthquake will grow may be influenced by operational factors under engineering control as well as natural tectonic factors. Determining the relative influence of these effects on maximum magnitude will impact the design and implementation of induced seismicity management strategies. In this work, we apply a numerical model that considers the coupled interactions of fluid flow in faulted porous media and quasidynamic elasticity to investigate the earthquake nucleation, rupture, and arrest processes for cases of induced seismicity. We find that under certain conditions, earthquake ruptures are confined to a pressurized region along the fault with a length-scale that is set by injection operations. However, earthquakes are sometimes able to propagate as sustained ruptures outside of the zone that experienced a pressure perturbation. We propose a faulting criterion that depends primarily on the state of stress and the earthquake stress drop to characterize the transition between pressure-constrained and runaway rupture behavior.

1. Introduction

Disposal of wastewater associated with oil and gas operations by injection into the subsurface is a common practice in the petroleum industry. Changes in the state of stress at depth caused by fluid injection have reportedly generated significant levels of seismic activity near Underground Injection Control (UIC) class-II wells in several instances (Barbour et al., 2017; Frohlich, 2012; Frohlich et al., 2014, 2011; Healy et al., 1968; Hornbach et al., 2015; Horton, 2012; Hsieh and Bredehoeft, 1981; Keranen et al., 2013; Kim, 2013; Rubinstein et al., 2014; Walsh and Zoback, 2015). In order to determine the seismic hazard for a site, it is important to estimate parameters in probabilistic seismic hazard assessment models, such as the maximum expected earthquake magnitude and the occurrence rate of a given-magnitude earthquake (Ellsworth et al., 2015). Understanding how the interaction between injection well operational parameters and natural geologic setting affects the behavior of induced earthquakes is difficult to quantify and has, so far, remained unresolved (Ellsworth, 2013; McGarr et al., 2015).

Apart from ground motion estimates, the most influential parameters in earthquake hazard analysis are the seismicity rate, the Gutenberg-Richter (GR) frequency-magnitude scaling factor, and the maximum earthquake magnitude (Petersen et al., 2014). If these earthquake statistics can be quantified accurately, then the data can be combined to develop a probabilistic estimate of earthquake hazard for a particular area. van der Elst et al. (2016) found that the maximum magnitude earthquakes observed in 21 separate cases of injection-induced seismicity were each as large as expected statistically based on the local earthquake catalogs. Characterization of the hydromechanical reservoir response to fluid injection must therefore be cast in terms of understanding how these types of earthquake statistics can be expected to change due to injection operations (Dempsey et al., 2016; Llenos and Michael, 2013).

Wastewater injection wells target injection horizons within naturally permeable brine aquifers, which are usually composed of sedimentary rocks. In most cases where relatively large earthquakes have been attributed to fluid injection, the earthquake hypocenters have been located beneath the target aquifers along faults that exist within igneous basement rocks (Horton, 2012; Kim, 2013; Keranen et al., 2014; Hornbach et al., 2015). It has been suggested previously that basement faults may sometimes extend into overlying formations, providing a necessary hydraulic connection for pressure communication (Ellsworth, 2013; Göbel, 2015; Göbel et al., 2016; Hornbach et al., 2015; McGarr, 2014). If the fluid pressure within a fault zone increases

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due to injection, the effective normal compressive stresses that provide resistance to shear slip are reduced, thereby bringing the state of stress on the fault closer to failure conditions (Ellsworth, 2013; Jaeger et al., 2007; Raleigh et al., 1976).

McGarr (2014) used an analytical poroelastic reservoir model and an assumption about the frequency-magnitude scaling of earthquake sequences to develop an expression for a theoretical upper bound on earthquake magnitude that was related linearly to the cumulative volume of injected fluid. An implicit assumption was made that earthquakes must be confined to regions that experience pressure change. In that study, it was concluded that data collected from 18 different case studies of injection-induced seismicity supported the proposed relationship between maximum magnitude and injection volume. In this perspective, the size of an earthquake is related closely to the injection operations. Göbel (2015) presented a comparison between induced seismicity in Oklahoma and California based on regional-scale statistics of earthquakes, injection rates, and injection pressures. In that study, it was concluded that differences in the geologic setting likely played the primary role in how injection-triggered seismicity has evolved in those study areas over the past two decades, and the influence of injection well operations was of secondary importance. In this work, we explored the relationship between fluid injection, flow through porous media, and earthquake rupture along faults through numerical modeling experiments.

2. Faulting criterion

In reservoir engineering, the “distance of investigation ” has been used to describe the location in the reservoir where pressure has changed by a prescribed magnitude and is often interpreted as a pressure front (Horne, 1995). It is intuitive to understand that the likelihood of interacting with hydraulic connections to basement faults increases as injection continues and the pressure front migrates further from the well. However, does this length-scale set a bound on the dimension of an earthquake rupture and, ultimately, the earthquake magnitude?

We addressed this question by performing numerical simulations that modeled the coupled interactions between fluid flow in porous media, fluid flow in faults, and earthquake rupture physics (McClure and Horne, 2011; Norbeck and Horne, 2016). We modeled a scenario where fluid was injected into a permeable aquifer overlying impermeable basement rock. A strike-slip fault zone in the vicinity of the well was located mostly within the basement rock, but a portion of the fault extended into the aquifer (see Fig. 1). The reservoir and fault geometry in our conceptual model were designed to be consistent with several recent instances of induced seismicity (Hornbach et al., 2015; Horton, 2012; Keranen et al., 2014; Kim, 2013). In contrast to previous studies, for example see McGarr (2014) and Barbour et al. (2017), we modeled the hydraulic interaction between the aquifer and the fault explicitly

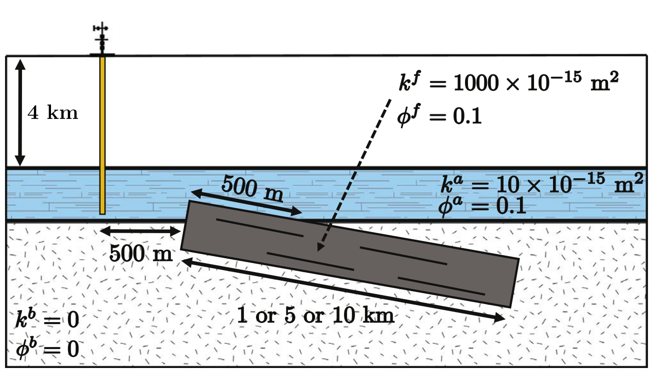

Fig. 1. Conceptual reservoir model used to design the numerical modeling experiments. A permeable basement fault extended slightly into a saline aquifer, allowing for pressure communication during fluid injection.

and considered a rigorous treatment of the earthquake rupture process within the framework of rate-and-state friction theory.

We propose classifying faulting behavior into two separate categories:

- *Pressure-constrained ruptures* (Type A) are limited by the extent of the pressure perturbation along the fault.
- *Runaway ruptures* (Type B) are controlled by traditional tectonic factors such as fault geometry or stress heterogeneity.

This is a useful distinction because pressure-constrained behavior might be considered more stable. For example, the maximum earthquake magnitude might be expected to grow over time in a systematic manner as larger patches of the fault are exposed to significant pressure changes. For runaway rupture behavior, although fluid injection may ultimately be responsible for causing earthquakes to nucleate, the factors controlling how large an earthquake will grow might depend more closely on characteristics of the natural geology, such as the size of the fault, geometric complexity, and stress heterogeneity.

We simulated sequences of injection-induced earthquake ruptures and found that the following faulting criterion, C, can be used to assess the conditions that separate the two categories of behavior:

$$C = \frac{f_0}{f_D}, \tag{1}$$

where f_D is the dynamic friction coefficient and $f_0 = \tau_0/\overline{\sigma}_0$ is the ratio of shear stress, τ_0, to effective normal stress, $\overline{\sigma}_0$, acting on the fault before injection begins (i.e., the prestress ratio). For $C < 1$, pressure-constrained behavior occurs within the pressure influenced region, and for $C > 1$, runaway rupture behavior occurs. This faulting criterion describes a subset of the transitional faulting behaviors investigated and quantified by Garagash and Germanovich (2012). As is discussed in Section 5.2, Eq. (1) can also be derived from an earthquake energy balance.

The parameter f_D can be estimated from rate-and-state friction laboratory experiments (Blanpied et al., 1991, 1995; Dieterich, 1992) or through controlled field experiments (Guglielmi et al., 2015). The parameter f_0 embodies the initial state of stress, the initial fluid pressure, and the orientation of the fault. In practical applications, there may be considerable uncertainty in the state of stress and frictional properties of real faults. However, in the numerical experiments we performed where the model properties were known with certainty, we found that the value of the faulting criterion in Eq. (1) was good indicator of whether earthquake ruptures would arrest within the pressure-perturbed region or propagate in a sustained manner beyond the pressure front.

3. Hydromechanical coupling with a rate-and-state friction model

We performed our numerical experiments with a reservoir modeling software called CFRAC (McClure and Horne, 2011, 2013; Norbeck, 2016; Norbeck et al., 2016). The simulations involved a coupling between fluid flow in an aquifer, fluid flow along a fault, and quasidynamic earthquake rupture. Mass transfer between the aquifer domain and the fault was calculated using an embedded fracture modeling approach (Karvounis and Jenny, 2016; Li and Lee, 2008; Norbeck et al., 2016; Ţene et al., 2017). Earthquake rupture, propagation, and arrest were considered within the context of a rate-and-state friction constitutive framework.

3.1. Fluid flow in faulted porous media

In the embedded fracture modeling framework, the mass conservation equations for the aquifer and fault domains are expressed separately which allows for flexibility in the discretization strategy