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Frictional stability and earthquake triggering during fluid pressure stimulation of an experimental fault

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ABSTRACT

It is widely recognized that the significant increase of $M > 3.0$ earthquakes in Western Canada and the Central United States is related to underground fluid injection. Following injection, fluid overpressure lubricates the fault and reduces the effective normal stress that holds the fault in place, promoting slip. Although, this basic physical mechanism for earthquake triggering and fault slip is well understood, there are many open questions related to induced seismicity. Models of earthquake nucleation based on rate- and state-friction predict that fluid overpressure should stabilize fault slip rather than trigger earthquakes. To address this controversy, we conducted laboratory creep experiments to monitor fault slip evolution at constant shear stress while the effective normal stress was systematically reduced via increasing fluid pressure. We sheared layers of carbonate-bearing fault gouge in a double direct shear configuration within a true-triaxial pressure vessel. We show that fault slip evolution is controlled by the stress state acting on the fault and that fluid pressurization can trigger dynamic instability even in cases of rate strengthening friction, which should favor aseismic creep. During fluid pressurization, when shear and effective normal stresses reach the failure condition, accelerated creep occurs in association with fault dilation; further pressurization leads to an exponential acceleration with fault compaction and slip localization. Our work indicates that fault weakening induced by fluid pressurization can overcome rate strengthening friction resulting in fast acceleration and earthquake slip. Our work points to modifications of the standard model for earthquake nucleation to account for the effect of fluid overpressure and to accurately predict the seismic risk associated with fluid injection.

1. Introduction

In recent years, human induced seismicity associated with underground wastewater disposal and fluid injection has become a matter of societal concern. Seismicity rates have increased dramatically in regions far from active tectonic margins, and stable continental regions like the Western Canada Sedimentary basin (e.g. Atkinson et al., 2016; Bao and Eaton, 2016) and the central United States (e.g. Keranen et al., 2014; Frohlich and Brunt, 2013; Ellsworth, 2013; Langenbruch and Zoback, 2016) have seen sharp increases of moderate to large earthquakes, with Mw >5 events becoming common. In Europe, induced earthquakes during fluid pressure stimulation of subsurface reservoirs have been documented in several notable cases including Switzerland (Deichmann and Giardini, 2009), southern Italy (Improta et al., 2015) and the Netherlands (van Thienen-Visser and Breunese, 2015).

Within plate interiors, surveys of crustal stress and measurements from deep boreholes have shown that the crust is critically stressed, with shear stress levels near the strength limit for brittle failure (Townend and Zoback, 2000). Under these conditions, the maximum stress level that can be supported is limited by the frictional strength of pre-existing ancient faults. Thus, even small changes in the stress field surrounding ancient faults can trigger earthquakes (Stein, 1999) (Fig. 1a). It has long been known that underground fluid injection can induce seismicity (e.g., Raleigh et al., 1976; Simpson et al., 1988). Long-term fluid injection at high rates nearby pre-existing faults can modify the surrounding stress field (either directly or indirectly) causing reactivation of preexisting faults (e.g., Ellsworth, 2013). The basic physical mechanism for inducing seismicity is well understood in terms of the effective stress principle (Hubbert and Rubey, 1959; Sibson, 1986):

$$\tau = C + \mu(\sigma_n - P_f) \quad (1)$$

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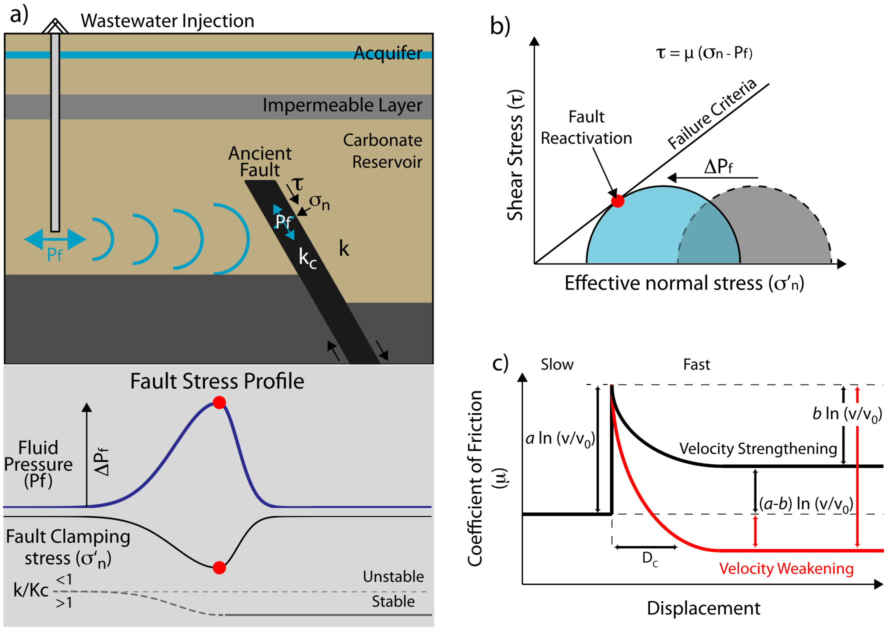

Fig. 1. Schematic illustrations of (a) mechanism(s) for induced seismicity associated with fluid injection and (lower panel) the stress state around an injection well. In response to fluid injection, the fluid pressure front diffuses and modifies the stress field around faults, causing fault reactivation. (b) Coulomb–Mohr diagram for shear failure and (c) the principles of rate- and state-friction (RSF). When the initial stress state of a fault, gray circle in (b), is perturbed by an increase in fluid pressure (ΔP_f), the conditions for fault reactivation are favored, blue circle in (b). Under these conditions, the fault frictional stability is evaluated via the RSF behavior (c). An increase in sliding velocity causes an instantaneous increase of the frictional strength that evolves in two main fashions. If the frictional strength increases the fault has the characteristic "velocity strengthening" behavior which leads to stable sliding (black line). Whereas, in the "velocity weakening" regime increased slip velocity causes a decrease in frictional strength, and the fault has the potential to nucleate a seismic instability (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where τ is the shear stress acting on the fault, C is cohesion, and μ is the coefficient of friction which is multiplied by the difference between the normal stress (σ_n) and fluid pressure (P_f), which represents the effective normal stress (σ_n'). During underground fluid injection, propagation of a fluid pressure front from the injection point reduces the effective normal stress acting on incipient fault planes, promoting earthquake failure (e.g. Hubbert and Rubey, 1959; Shapiro and Patzig, 2003; Keranen et al., 2014; McGarr, 2014; Bao and Eaton, 2016) (Fig. 1a and b).

The Coulomb failure relation of Equation (1) predicts the stress conditions for fault slip (Fig. 1b) but it does not address the question of frictional stability and whether slip will be seismic or aseismic upon reactivation. The stability of frictional sliding is determined by the local elastic stiffness around the fault and the fault zone friction constitutive properties (Rice and Ruina, 1983). Rate- and state-frictional (RSF) constitutive equations are commonly employed to describe fault friction and the resulting slip behavior (Dieterich, 1979; Ruina, 1983; Marone, 1998):

$$\mu = \mu_0 + a \ln\left(\frac{v}{v_0}\right) + b \ln\left(\frac{\theta v_0}{D_c}\right) \tag{2}$$

where, upon a velocity increase from v_0 to v, the coefficient of friction (μ) suddenly increases (direct effect, a) from a reference steady state (μ_0) and then evolves to a new steady state (evolution effect, b) over a characteristic critical slip distance (D_c) (Fig. 1c). The state variable, θ is commonly interpreted as the average lifetime of frictional contacts and it evolves over the critical slip distance D_c following a state evolution law such as (Ruina, 1983; Marone, 1998):

$$\frac{d\theta}{dt} = -\frac{v\theta}{D_c} \ln\left(\frac{v\theta}{D_c}\right) \tag{3}$$

Under conditions of steady state shear $d\theta/dt = 0$ and $\theta_{ss} = D_c/v$. The dependence of frictional strength on slip rate is described by the friction rate parameter $(a - b) = \Delta\mu_{ss}/\log(v/v_0)$. If friction increases with increasing velocity, $(a-b) > 0$, the material is velocity strengthening and slip is inherently stable, leading to aseismic fault creep (Fig. 1c). However, if the material is velocity weakening, $(a - b) < 0$, frictional strength decreases with slip velocity and slip may be unstable, satisfying the conditions for the nucleation of a seismic instability, depending on the rate of weakening with slip $(b - a)/D_c$.

Combining elastic dislocation theory with RSF constitutive equations provides a general description for the criterion of fault stability (Ruina, 1983; Gu et al., 1984). For a velocity weakening fault gouge, a dynamic frictional instability will nucleate when the stiffness of the loading system, k, is lower than a critical fault rheologic stiffness, k_c, defined by:

$$k_c = (\sigma_n - P_f)(b - a)/D_c \tag{4}$$

Equation (4) shows that an increase in fluid pressure reduces k_c, favoring stable sliding rather than earthquake slip (Fig. 1a). This prediction contrasts with seismological observations that show a strong link between massive fluid injection and induced seismicity. We note that a modification of the RSF laws accounts for the role of normal stress changes, which could destabilize slip (Linker and Dieterich, 1992), however 1) this additional term does not impact the stability boundary significantly and 2) additional laboratory data are needed to assess the role of normal stress perturbations on the evolution of frictional strength (e.g., Kilgore et al., 2017).

In addition, Equation (4) predicts earthquake slip only if the fault has a velocity weakening behavior, i.e. $(b - a)$ positive, while laboratory experiments show that at stress/temperature conditions typical of the occurrence of induced seismicity, i.e. <5 km, a wide variety of fault gouge materials show velocity strengthening frictional behavior (e.g. Blanpied et al., 1998; Ikari et al., 2011; Samuelson and Spiers, 2012; Scuderi et al., 2013; Kohli and Zoback, 2013). However, recent experimental studies under conditions of controlled pore fluid pressure, have shown that the increase in