Effect of Permeability Evolution in Fault Damage Zones on Earthquake Recurrence

Zhuo Yang1, Alissar Yehya2,3, Tajudeen M. Iwalewa2, and James R. Rice1,2

1Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA, 2School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA, 3Department of Civil and Environmental Engineering, American University of Beirut, Beirut, Lebanon

Abstract Micro-crack density, porosity, and permeability in fault damage zones play an important role in the pore fluid diffusion process. During long-term earthquake cycles, those properties change with time as a result of either physical damage or chemical/physical healing. Hence, the evolution of permeability can affect the recurrence of earthquakes by either delaying or accelerating the weakening of the fault core through controlling the pore pressure distribution and changing the effective normal stress. In this study, we use a single degree of freedom spring slider analog fault model to simulate the earthquake sequences, considering permeability as a decreasing function of the effective normal stress and thus an increasing function of pore pressure; we also examine its evolution resulting from coseismic damage and interseismic healing. Our simulation results show that different permeability evolution, controlled by various physical conditions, could result in a variety of fault slipping histories, which demonstrates the importance of incorporating the permeability evolution into earthquake modeling, especially when assessing the long-term effects.

Plain Language Summary The strength of a fault is mainly determined by the shear stress and the effective normal stress. The change in effective normal stress may come from the change in pore pressure, which is determined by fluid flow in fault zones. Fluid flow and diffusion are further controlled by the permeability structure of the fault. In traditional earthquake modeling frameworks, the permeability is often regarded as a constant, however, the permeability will change due to a variety of processes including mechanical damage during earthquakes and chemical healing between subsequent earthquakes. In this study, we propose a new modeling framework using a spring slider fault model with permeability evolution during the earthquake cycles. Our model shows that the permeability evolution under different physical conditions could result in different earthquake recurrence patterns. Such results reveal the importance of considering permeability evolution in earthquake simulations and help us gain more insights in earthquake risk assessments.

1. Introduction

The strength of a fault is mainly determined by its friction properties and stress state. Variations of pore pressure on the fault plane will either weaken or strengthen the fault. Since the fluid flow in the subsurface is largely controlled by the permeability structure, especially in the fault damage zones, the evolution of the permeability will cause changes in pore pressure and further influence the occurrence of earthquakes (Aochi et al., 2014; Cappa, 2009; Cruz-Atienza et al., 2018; Rice, 2006; Segall & Rice, 1995; Walsh & Zoback, 2015; Yehya et al., 2018; Zhu et al., 2020). Various factors control the nature of damage zones around faults, namely, lithology, the dip of bedding relative to the slip direction of the fault, and the stress system (Kim et al., 2004). The fault core and the damage zones reflect the mechanical deformation and chemical conditions within a fault zone. Whether a fault zone acts as a conduit, barrier, or combined conduit-barrier system is controlled by the sizes of the damage zone and the fault core with respect to the fault structure and its corresponding permeability (Caine et al., 1996). During deformation the fault might conduct fluids, and then act as a barrier when open pore spaces are filled by mineral precipitation following deformation. Thus, it is essential to specify the stage of fault evolution to understand the fault zone permeability structure. Permeability values of laboratory samples from natural fault core materials show a range of variation between $10^{-22}$ to $10^{-12}$ m² (Smith & Evans, 1984). This suggests that the permeability of the fault core depends on...
the lithology and on the degree of mechanical and chemical alteration that this lithology has undergone (Caine et al., 1996).

Micro-crack density, porosity, and permeability structure play an important role in the pore fluid diffusion process. The temporal and spatial evolution of permeability (deformation/healing dependent) is important to better assess the effects of fluid injection or pressure perturbation on nearby faults (Yehya et al., 2018). In some cases, healing of micro-cracks in damage zones can create a barrier to fluid flow to delay pore pressure diffusion and the pressurization of the fault core (Yehya & Rice, 2020). On the other hand, the enhancement of permeability by deformation under high pore pressure from fluid injection rapidly facilitates the pressurization of the fault core. Hence, the permeability evolution (deformation/healing) can affect the recurrence of earthquakes by either delaying or accelerating the weakening of the fault core through increasing or reducing the effective normal stress, respectively.

As supported by laboratory studies (Brace, 1978, 1980; Brace et al., 1968; Huenges & Will, 1989; Pratt et al., 1977), the permeability is a strongly decreasing function of the effective normal stress, though its variation is not only limited to that. This makes it important to understand the range of effective normal stresses over which there is a transition from continuously permeable to rapidly sealed response through the earthquake cycle (Rice, 1992). This is discussed further in the coming sections.

To study, in a simple setting, the effect of permeability evolution (pores, micro-cracks) in damage zones, on earthquake recurrence, we use a single-degree of freedom spring-slider analog fault model. For the evolution of permeability, we employ the Rice (1992) model, which postulates that permeability is dependent on the effective normal stress (hence on the pore pressure). Besides, other mechanical and chemical processes can also change the permeability, so we add, in our permeability model, the effect of two dominant factors, which are coseismic deformation and interseismic healing. When pressure perturbation occurs, the elevated pore pressure is diffused depending on the hydraulic properties of the rock matrix. Therefore, our focus is on the cases that involve pressure perturbations that can diffuse into the fault structure. Fluid transport in the crust leads to a competition between depositional processes, which reduce the permeability (Smith & Evans, 1984), and rupture processes, which renew pore connectivity as a result of shear failure and local tensile cracking, driven by pressure build-up along flow pathways (Fyfe et al., 1978; Nur & Walder, 1990; Rice, 1992). Thus, the pore pressure distribution should be treated as time dependent. A plausible assumption in many cases is that there is a source providing fluids deep in the crust near the ductile root of the fault zone (Rice, 1992). As long as the pore pressures are high and approach lithostatic values, the pores will remain open; otherwise, the pore spaces will close by the creep effect (Renard et al., 2000).

There are different kinds of fluid sources that could potentially contribute to the increase of pore pressure on fault interfaces. These sources can be natural sources, such as strong precipitation in Alpine fault in New Zealand (Boulton et al., 2017), dehydration of slabs in subduction zones (Fulton & Saffer, 2009) or anthropogenic sources such as injected wastewater in oil and gas fields (Frohlich et al., 2011; Healy et al., 1968; Horton, 2012). Due to the different types of fluid sources, the spatial and temporal scales can be different, resulting in different pore pressure changes on faults planes, which may change the reoccurrences of earthquakes in different ways (i.e., either accelerate or delay the recurrence of earthquakes).

The main objective of this work is to use a simple model to investigate the effect of permeability evolution on the earthquake cycle in the presence of pore pressure diffusion. The proposed spring-slider model is coupled with the diffusion equation having a temporally evolving diffusivity. The variation in diffusivity reflects the permeability evolution from both damage and healing processes.

### 2. Permeability Evolution

We model the fault zone permeability as a decreasing function of the effective normal compressive stress and, thus, an increasing function of the pore pressure. The permeability of a medium with high density of open fractures (low value of the bulk modulus at zero confining pressure) shows a greater sensitivity to effective normal stress than rocks of higher bulk modulus (Huenges & Will, 1989). This leads to the below approximate representation (Rice, 1992),

\[
 k = k_0 \exp\left(-\frac{\sigma_n}{\sigma^*}\right)
\]  

(1)
\[
\sigma_n' = \sigma_n - p
\]  
(2)

where \(k_0\) is the permeability at zero effective normal stress, \(\sigma^*\) is a constant, \(\sigma_n\) is the effective normal stress, \(\sigma_n'\) is the normal stress, and \(p\) is the pore pressure. The significance of \(\sigma^*\) is to describe the dependence of the permeability on the effective normal stress. Low values of \(\sigma^*\) mean higher sensitivity to \(\sigma_n'\), which correlates, based on experiments, with higher fracture density and higher \(k_0\). Based on Rice (1992), in the actual situation of a fault zone, where the permeability is a result of the competition between healing/depositional sealing and rupturing to renew pore connectivity, the strong dependency of the permeability \(k\) on pore pressure would mean that \(k\) is negligible unless \(p\) goes up toward the normal stress (lithostatic pressure). To reflect this situation, \(\sigma^*\) should have a low value. Hence, the parameter \(\sigma^*\) denotes the range of the effective normal stresses over which there is a transition from rapidly sealed to continuously permeable response (Rice, 1992).

In order to estimate \(k_0\), we take into consideration the dynamic rupture during coseismic periods and the thermal enhanced healing during interseismic periods. The energy in earthquakes partitions into fracture energy, radiated energy, and heat energy (Venkataraman & Kanamori, 2004). We estimate the newly opened void spaces based on the numerical simulations of fault dynamic rupture by Okubo et al. (2019). Off-fault damage contributes to approximately 4%–34% of the fracture energy, and we use 15% as an average in our simulations. Among newly opened fractures, around half of them are tensile fractures, which could change the porosity of the medium. To estimate the size of the newly opened cracks, we adopt the cohesion model in Okubo et al., (2019) and assume that all the cracks are fully opened to the critical opening displacement \(\delta_{IC}^c\). Therefore, we calculate the increase of porosity as:

\[
\Delta \phi = \frac{\Delta E_I}{G_{IC}} \times \frac{\delta_{IC}^c}{w}
\]  
(3)

where \(\Delta E_I\) is the off-fault fracture energy (for tensile cracks) released per unit area on the fault plane, \(G_{IC}\) is the fracture energy for tensile cracks, \(\delta_{IC}^c\) is the critical opening displacement, and \(w\) is the width of the fault-bordering damage zone. Then, we calculate the change of permeability in the damage zone by accounting for the change of porosity based on the model developed in Chin et al. (2000):

\[
\phi_d = \phi_i + \Delta \phi
\]  
(4)

\[
k_d = k_i \left( \frac{\phi_d}{\phi_i} \right)^n
\]  
(5)

where \(\phi_d\) and \(k_d\) are the porosity and permeability after coseismic damage, \(\phi_i\) and \(k_i\) are the initial porosity and permeability before the earthquake, and \(n\) is the cementation exponent that ranges for most rocks between 1.7 and 4.1 (Verwer et al., 2011). In our simulation, we choose \(n\) to be 3, which is plausible for most types of rocks.

During the interseismic period, healing of the micro-cracks in damage zones may occur in the presence of fluids. Unlike the case of a dry matrix, where healing does not occur unless the crack faces are in contact, fluid circulation facilitates the diffusive mass transport and accelerates the healing rates. This could be either by surface diffusion or by dissolution and precipitation under elevated temperatures. Fluid assisted healing is thermally activated and enhanced by local changes in temperature induced by warm fluid migration (Yehya & Rice, 2020). Hence, the crack lifetime can be expressed as (Smith & Evans, 1984):

\[
\lambda(T) = \frac{\lambda_0 T}{T_0} \exp \left( \frac{Q}{R \left( \frac{1}{T} - \frac{1}{T_0} \right)} \right)
\]  
(6)

where \(\lambda\) is the crack lifetime, \(T\) is the local temperature, \(Q\) is the activation energy for surface diffusion, \(R\) is the gas constant, \(\lambda_0\) and \(T_0\) are, respectively, the reference crack lifetime and the reference temperature obtained from experiments (Smith & Evans, 1984). The significance of this equation is that a crack at temperature \(T\) needs time \(\lambda_0\) to heal. Therefore, the same crack will need a time equal to \(\lambda\) (obtained from Equation 6) to heal at an arbitrary constant temperature \(T\). Since Equation 6 is derived for constant temperature,
Engvik et al. (2009) obtained a dimensionless crack lifetime healing parameter for a temporally varying temperature, which is defined as:

$$ z = \int_{t_0}^{t} \frac{1}{\lambda(T)} dt $$

(7)

where $t_0$ represents the time when the crack has been created and $t$ represents the current time. If temperature $T$ does not change with time, the calculation of $z$ could be simplified to $z = \frac{t - t_0}{\lambda(T)}$. And consequently, the porosity $\phi_0(t)$ and the permeability $k_0(t)$ are expressed as:

$$ \phi_0(t) = \phi_d \left(1 - z^n\right) $$

(8)

$$ k_0(t) = k_d \left(\frac{\phi_0(t)}{\phi_d}\right)^n $$

(9)

where $\phi_0$ and $k_0$ are, respectively, the porosity and permeability at zero effective stress, $\phi_d$ and $k_d$ are the porosity and permeability after earthquakes but before healing, $n_0$ is a dimensionless constant obtained from experiments and related to the geometry and rock type. Inserting Equation 9 in Equation 1, we get the evolving permeability as a combination of the damage in the coseismic phase, the healing during the interseismic period, and the effect of the effective normal stress.

### 3. Spring Slider Model Coupled With Fluid Diffusion and Permeability Evolution

The spring slider model simulates the friction contact surface with a spring representing the elasticity of the earth’s crust and a constant load point velocity, mimicking the constant plate motion that supplies energy to the plate boundary faults in the earth. We assume that the slipping zone is bordered by high permeability damage zones (Figure 1). If fluid perturbation occurs near the fault, the damage zones would act as conduit structures to diffuse the fluid pore pressure to the fault slipping zone (Yehya et al., 2018). Hence, the permeability of the fault damage zone, which is determined by the interconnecting micro-cracks, is an important factor to change the pore pressure on the fault plane.

The constitutive law that governs the fault is the rate- and state-dependent friction law, as enhanced to incorporate the effect of variable effective normal stress. The pore pressure is temporally variable assuming a pressure perturbation exists at a certain distance from the fault. The modified state evolution law from Rice et al. (2001) gives,

$$ \frac{d\theta}{d\tau} = g_1(v, \theta) + \frac{d\sigma_n}{d\tau} g_2(\sigma, v, \theta) $$

(10)

with $g_1(v, \theta) = 1 - \theta v/d_c$ from the aging law and $g_2(\sigma, v, \theta) = -a\theta/bs$ from Linker and Dieterich (1992), and $\sigma_n$ being the effective normal stress as defined in Equation 2, $v$ being the slip velocity, $\theta$ being the state variable, $d_c$ being the characteristic displacement scale, $a$ being the coupling parameter between effective normal stress and the state variable, $b$ (mentioned in the following equation) and $c$ are rate and state friction parameters. The modified constitutive law becomes:

$$ \tau = \sigma_n \left[ f_0 + a \log \frac{v}{v_0} + b \log \frac{\theta}{\theta_0} \right] $$

(11)

$$ \frac{d\theta}{d\tau} = 1 - \frac{\theta v}{d_c} - \frac{a\theta}{b\sigma_n} \frac{d\sigma_n}{d\tau} $$

(12)
Equations 11 and 12 are rewritten in terms of \( \psi = f_0 + b \log \frac{\theta}{\theta_0} \). Besides, we add a regularized term accounting for the backward microscopic jumps (Lapusta et al., 2000), which gives the final equations to be solved:

\[
\tau = \sigma_n' a \sinh^{-1}\left(\frac{\psi}{2v_0}\right) \exp\left(\frac{\psi}{a}\right)
\]

(13)

\[
\psi = \frac{hv_0}{d} \left(\exp\left(\frac{f_0 - \psi}{b}\right) - \frac{\psi}{v_0}\right) \frac{\alpha}{\sigma_n'} \frac{d\sigma}{dt}
\]

(14)

To calculate \( \sigma_n' \), we need to calculate the pore pressure. For this, we couple the model with a 1D diffusion equation having spatially and temporally varying permeability and porosity:

\[
\frac{\partial p}{\partial t} = \frac{1}{\phi c, \mu c x} \left( k \frac{\partial p}{\partial x}\right)
\]

(15)

where \( k \) and \( \phi \) are calculated using the damage and healing equations, while also incorporating the effect of effective normal stress, \( \mu \) is the fluid viscosity and \( c \) is the sum of rock and fluid compressibility. We calculate the hydraulic diffusivity \( D \), as \( D = k/(\mu c \phi \phi) \).

To simulate the movement of the spring slider, we need to solve the equation of motion at each time step. Rather than solving for \( mdv/dt \), we use the radiation damping approximation to replace it, and the equation becomes:

\[
\tau_{qs} - \tau = \eta v
\]

(16)

where the \( \tau_{qs} \) is the quasi-static shear stress of the spring, \( v \) is the velocity of the slider and \( \eta = G/2v_l \), \( G \) is the shear modulus and \( v_l \) is the shear wave velocity (Rice, 1993). In our model, the quasi-static shear stress comes from remote loading, which can be expressed as: \( \tau_{qs} = k_{spring} \delta \), where \( \delta \) is the slip distance of the slider.

We use LSODA, an ordinary differential equation solver for stiff or non-stiff systems (Hindmarsh, 1983), to solve for the slip \( \delta \) and the state variable \( \psi \) at each time step, while updating all other parameters. From time step \( t \) to \( t + \Delta t \), we update the system by the following procedure:

1. Update permeability \( k(t) \)
   a) Calculate the permeability change due to the change of effective normal stress \( \sigma_n = p(t + \Delta t) \) by Equation 1
   b) Right after the end of coseismic period, increase the permeability and porosity due to dynamic rupture following Equations 3–5
   c) During the interseismic period, decrease the permeability due to the thermal enhanced healing following Equations 6–9 until the porosity and permeability drop back to the initial values.

2. Solve the fluid diffusion Equation 15 for pore pressure \( p(t + \Delta t) \) using the finite volume approach (Guyer et al., 2009). The time step \( \Delta t \) from the spring slider solver is further divided into more steps to solve the diffusion equation.

3. Take the updated pore pressure on the fault plane in Equations 13 and 14 to calculate the velocity \( v \) of the spring slider and the gradient of the state change \( \psi \)

In order to ensure the accuracy and stability of the simulations, we keep increasing the number of steps to solve the diffusion equation until the simulation results become stable (i.e., the results stop changing when we decrease the time step). For each simulation, we first record the time when earthquakes happen in the reference model, which has no pore pressure perturbation. Then, we set the time of earthquakes, as well as the injection start and end time, to be the critical time points when solving the spring slider system, where the integration care will be taken (Ahnert et al., 2011; Hindmarsh, 1983).

At the beginning of each simulation, we set initial values for the permeability and porosity, which represent the minimum bound on permeability and porosity. We focus on modeling the thermal enhanced healing for the additional cracks created due to dynamic ruptures; therefore, the permeability and porosity will not drop lower than the initial values. In real fault damage zones, the rocks are often composed of a variety of
minerals, and the cracks often have different shapes and curvature; thus, some cracks take much longer time to heal, and the porosity and permeability are not expected to drop to zero. Besides, dynamic strains generated by other sources (e.g., seismic waves from other faults, tidal waves, etc.) will also cause opening of cracks in the damage zones and keep a non-zero porosity and permeability.

In the following simulations, the slider starts with an initial position at $x = -10 \text{ m}$, which has already accumulated some elastic energy, and an initial velocity $v$ equal to 0.0001 of the plate motion velocity. We run the simulations from $t = 0$ to $t = 3000$ years.

4. Simulation Results

A general fault structure contains a narrow fault core surrounded by highly permeable damage zones, where the permeability could be orders of magnitude larger than that in the fault core and host rocks (Mitchell & Faulkner, 2012). Since the damage zones are generally wider than the fault cores while having the largest permeability evolutions, we ignore the narrow fault cores in the following simulations. Therefore, we assume a width of $w = 200 \text{ m}$ for the damage zones surrounding the fault planes.

Based on the permeability evolution discussed in previous sections, we expect that the permeability in damage zones will increase due to dynamic rupture during coseismic periods, while it will decrease due to the thermally enhanced healing during interseismic periods. Besides, the permeability is also dependent on the evolution of the effective normal stress. In this work, we study two scenarios. The first, (a), focuses on the short-period, intense pore pressure perturbation, which often happens during wastewater injection near oil and gas fields. The second, (b), scenario focuses on the long-period, small pore pressure perturbation, which are closely related to dehydration processes near subduction zones. The parameters used in the simulations are summarized in Table 1.

4.1. Scenario 1: Wastewater Injection

As shown in Figure 2, the first scenario represents wastewater injection near a fault zone, which commonly happens in oil and gas fields. Wastewater injection has been identified as one of the major reasons for triggering earthquakes in many fields around the world (Frohlich et al., 2011; Goebel & Brodsky, 2018; Healy et al., 1968; Horton, 2012). The mechanism of such induced earthquakes relates to the change of the effective normal stress due to pore pressure perturbation from wastewater injections. Many previous works have been done to study the triggering process, as well as the relatively short period influence on the stress field due to wastewater injection (Chang & Segall, 2016; Ellsworth, 2013; Yehya et al., 2018; Zhai et al., 2019). In this scenario, we focus on studying the long-term effect of such short-period, high-intensity pore pressure perturbations on earthquake recurrence.

We assume the injection happened at the center of the fault zones, which are primarily formed with highly fractured, high permeability damage zones, and surrounded by low permeability host rock. Although such scenario rarely happens in reality, it is a good approximation to many real cases since injection wells could be located very close to nearby unknown faults (Keranen et al., 2013; McNamara et al., 2015; Yeo et al., 2020) or inject into a high permeability reservoir layer right above the fault zones (Horton, 2012). The initial permeability distribution is summarized by Equation 17

$$k_i(t = 0) = \begin{cases} 1.28 \times 10^{-14} \text{ m}^2, & |x| < 100 \text{ m} \\ 1.28 \times 10^{-18} \text{ m}^2, & |x| \geq 100 \text{ m} \end{cases}$$

(17)

where $|x| < 100 \text{ m}$ represents the area within damage zones and $|x| \geq 100 \text{ m}$ represents area within host rock. The permeability distribution in the whole field changes with the change of the effective normal stress following Equation 1, and the permeability within the damage zones also changes due to the dynamic rupture and the thermally enhanced healing. We assume the fault is located at a depth of 3 km with the initial effective normal stress $\sigma_n = 51 \text{ MPa}$. The loading spring constant is $k_{spring} = 3 \text{ MPa/m}$. The injection, with pressure $\Delta p = 2 \text{ MPa}$, starts at $t = 860$ y and stops at $t = 862$ y.
| Parameter                                | Symbol | Value in scenario 1 | Value in scenario 2 |
|-----------------------------------------|--------|---------------------|---------------------|
| Shear modulus                           | $G$    | $3 \times 10^{10}$ Pa | $3 \times 10^{10}$ Pa |
| Rock density                            | $\rho_r$ | 2,700 kg / m$^3$ | 2,700 kg / m$^3$ |
| Rate of plate motion                     | $V_p$  | $10^{-9}$ m / s | $10^{-9}$ m / s |
| Characteristic displacement scale       | $d_c$  | 0.1 m | 0.1 m |
| Rate and state friction parameter       | $a, b$ | 0.015, 0.025 | 0.025, 0.035 |
| Loading spring constant                 | $k$    | 3 MPa / m  | 7.5 MPa / m  |
| Temperature                             | $T$    | 45°C | 50°C |
| Reference crack lifetime$^a$             | $\lambda_0$ | 400 yrs | 400 yrs |
| Reference crack temperature$^a$          | $T_0$  | 40°C | 40°C |
| Activation energy for surface diffusion$^a$ | $Q$    | 50,000 J/mol | 50,000 J/mol |
| Initial porosity                        | $\phi_0$ | 0.01 | 0.01 |
| Fluid viscosity                         | $\mu$  | $10^{-3}$ Pa s | $10^{-3}$ Pa s |
| Fluid compressibility                   | $\beta$ | $6.4 \times 10^{-10}$ Pa$^{-1}$ | $6.4 \times 10^{-10}$ Pa$^{-1}$ |
| Coupling between normal stress and state variable$^b$ | $\alpha$ | 0.53 | 0.53 |
| Reference value for the normal stress$^c$ | $\sigma^*$ | 20 MPa | 20 MPa |
| Initial effective normal stress         | $\sigma_0$ | 51 MPa | 145 MPa |
| Fracture energy for tensile cracks$^d$   | $G_{IC}$ | 1.48 kJ / m$^2$ | 1.48 kJ / m$^2$ |
| Critical opening displacement$^c$        | $\delta_{IC}^{cc}$ | 0.37 mm | 0.37 mm |
| Damage zone width                       | $w$    | 200 m | 200 m |
| Permeability-porosity exponent          | $n$    | 3 | 3 |
| Healing exponent$^a$                     | $n_h$  | 0.4 | 0.4 |
| Nominal coefficient of friction         | $f_0$  | 0.6 | 0.6 |
| Shear wave velocity                     | $v_s$  | 3.33 km/s | 3.33 km/s |

$^a$Yehya and Rice (2020), $^b$Linker and Dieterich (1992), $^c$Rice (1992), $^d$Okubo et al., (2019).
The simulation results of the spring slider are summarized in Figure 3, and the pore pressure, permeability and hydraulic diffusivity evolution are shown in Figure 4. In Figure 3a, we plot the slip velocity based on two models, among which one reference model (denoted as \( \bar{V} \)) does not incorporate the pore pressure perturbation, and the other model (denoted as \( pV \)) takes into account the permeability evolution described in Section 3 and the pore pressure perturbation. Based on the displacement history and the recurrence interval, we can see that the fluid injection could trigger an earthquake shortly after the start of the injection when the background shear stress is high enough, which makes the “expected earthquake” happen sooner and cause a sudden decrease of the recurrence interval \( T_p \). Following the injection, the pore pressure decreases quickly, but remains higher than the initial value, which weakens the fault plane by reducing the effective normal stress. Consequently, the earthquake recurrence interval is decreased from around 148.0 years at the beginning of the simulation to around 145.7 years at the end of the simulation time, which is shown in Figure 3b.

Figure 3. Simulation results of scenario 1 on slip velocity (m/s) and recurrence time interval (yrs). In (a), \( pV \) represents the simulation result of the model which incorporates the permeability evolution and fluid injection, and \( \bar{V} \) represents the result of a reference model which has time independent permeability and has no pore pressure perturbation. In (b), earthquake recurrence time intervals represent the time span between the current earthquake time and the previous earthquake time. Similarly, \( T \) represents the result of the model with permeability evolution and pore pressure perturbation, and \( T_p \) represents the result of the reference model.
As injection starts at $t = 860$ y, the pore pressure increases sharply. Since the total injection time is 2 years, which is relatively short compared to the long earthquake cycle simulation time, the pore pressure starts decreasing immediately after the injection stops. The permeability change is relatively small compared to its original value and will recover to its original level due to the fast healing rate. Thus, it has a little influence on the earthquake cycle following each coseismic rupture. While the evolution of intrinsic permeability $k_0$ represents the evolution of permeability due to dynamic rupture and thermal enhanced healing, the evolution of hydraulic diffusivity also incorporates the effect of changing effective normal stress. In Figures 4b and 4c, we can see that each earthquake will cause a sudden increase of the permeability and hydraulic diffusivity, then, they will gradually decrease due to interseismic healing. In this example, the healing rate is pretty fast so that it will decrease to the initial value in a short time, and more gradual drops in permeability are shown in the following examples (e.g., Figures 7 and 9). Besides, as plotted in Figure 4c, we can see...
that the hydraulic diffusivity increases significantly after fluid injection, which is due to the sudden increase in pore pressure.

4.2. Scenario 2: Subduction Zone Dehydration

In scenario 2, which is illustrated in Figure 5, fluid water could be generated in the subduction zones from dehydration of slabs, which could elevate the pore pressure at a certain depth (Fulton & Saffer, 2009). Given such fluid flow near seismogenic zones, fault planes can be weakened by the reduction of effective normal stress, and the evolution of permeability structure in the fault damage zones could also influence the fluid distribution along the fault.

In this scenario, we simulate the fluid diffusion in a subduction slab with a 30° dipping angle. The length of the slab is 50 km, and the width of the damage zone is 200 m. A fluid source is located at the bottom of a long damage zone with a flux \( q = 3 \times 10^{-10} \text{ m/s} \) (Kennedy et al., 1997). The initial permeability distribution in the damage zone is described by Equation 18:

\[
k(t = 0) = 2.57 \times 10^{-12} \times e^{-0.073z/12} \text{ m}^2
\]

where \( z_0 = 1 \text{ m} \) is a unit length and \( z \) is the depth ranging from \( z = 0 \) at the surface to \( z = 25 \text{ km} \) at the bottom of the slab. The permeability decreases as depth increases, which is an approximation to account for the effect of varying damage zone width, where damage zones are often narrower at deeper depth (Perrin et al., 2016), and their permeability is lower due to higher normal stresses. Since the influence of effective normal stress has been accounted for in Equation 18, as for the permeability evolution in the following simulations, we should only calculate the difference between the pore pressure and its initial stationary value (i.e., \( \Delta p = p(t) - p_0 \), where \( p_0 \) is the stationary pore pressure given at constant flux \( q \) without considering permeability evolution). Similar to scenario 1, the permeability is dependent on the change of effective normal stress based on Equation 1, and the permeability within the seismogenic zone, ranging from 5 to 15 km depth, also changes due to the dynamic rupture and the thermal enhanced healing. Pore pressure at depth \( z = 10 \text{ km} \) has been used to represent the average pore pressure in the seismogenic zone in the spring slider model.

The simulation results of the spring slider are depicted in Figure 6, and the pore pressure, permeability, and hydraulic diffusivity evolution are shown in Figure 7. Similar to scenario 1, the slip velocity has been plotted for two models, namely, a reference model that does not have permeability evolution, and another that incorporates permeability evolution described in Section 3. Even without pore pressure perturbation, the pore pressure distribution could still change due to the permeability evolution, which also influences the strength of the fault plane. At the beginning of the simulation, the coseismic dynamic rupture increases the permeability; thus, the pore pressure decreases. The initial relatively lower permeability, before rupture, caused a pressure build-up due to the trapped fluids within the fault zone. The increase in the permeability after rupture facilitates the diffusion of the pore pressure and released the pressure build-up. Therefore, the large drop in pore pressure strengthens the fault and cause a sudden increase of earthquake recurrence time interval. Such change may seem small at the beginning where we barely see any changes in the slip velocity variation of the spring slider in Figure 6a, the model considering permeability evolution gradually deviates from the reference model where no permeability evolution has been implemented. Near the end of the simulation period, we can observe that the recurring earthquakes have been delayed due to restrengthening of the fault plane by increasing the effective normal stress, which is also reflected as the earthquake recurrence interval increases compared with the reference model as shown in Figure 6b.

Pore pressure in the seismogenic zone decreases following permeability increases. Following the first earthquake, the permeability increases due to newly open cracks by dynamic rupturing, and the pore pressure drops with \( \Delta p = 2.5 \text{ MPa} \) accordingly. After a few recurring earthquakes, the pore pressure oscillates between a narrow range, which is around 3 MPa less than the initial stationary pore pressure, and stays in
Between each repeating earthquake, the permeability will increase sharply and decrease gradually back to its original value. It is important to note that when the permeability recovers to the initial value, the pore pressure does not have enough time to recover to the stationary value. Therefore, in order to estimate the pore pressure distribution more accurately, it is necessary to consider the fault’s slipping history as well as the permeability evolution instead of assuming a constant permeability.

5. Discussion

5.1. Effect of Country Rock Permeability in Scenario 1

Based on the simulation results shown in Figure 4, the pore pressure sharply decreases to a lower level after the end of injection, then decreases more slowly as time goes by and stays relatively stable at the lower level. However, the pore pressure is still higher than in the initial equilibrium state, which causes the weakening of the fault plane in a much longer time scale and decreases the periods between each repeating earthquake. Besides the permeability structure in damage zones, another important factor, which controls the pore pressure in fault planes, is the permeability of the country/host rock. Highly permeable host rock could allow injected fluid to diffuse quickly into the surrounding areas which will lower the pore pressure on the fault.
To analyze the effect of the permeability in country rock, we run scenario 1 with two different permeability values in the country rock. The low-permeability model has country rock permeability as $k = 1.28 \times 10^{-19} \text{ m}^2$, and the high-permeability model has country rock permeability as $k = 1.28 \times 10^{-18} \text{ m}^2$. Except for the permeability value in the country rock, both models share the same parameters as in scenario 1.

From the results shown in Figure 8, we find that the excess pore pressure, after the end of injection, is higher in the low-permeability model than the high-permeability model. Besides, the pore pressure in the high-permeability model also decreases much faster. Due to the differences of pore pressure, the relative displacements of the two models are also very different. In the low-permeability model, the fault plane is weakened substantially, so that the earthquake cycle is accelerated and the period between each repeating

Figure 7. Simulation results of scenario 2 on (a) evolution of pore pressure $p$, (b) evolution of permeability $k_0$ at zero effective stress and (c) evolution of hydraulic diffusivity. Note (b) only accounts for permeability evolution due to deformation damages and healing, but (c) also includes the influence of effective normal stress (i.e., due to the change of pore pressure).
earthquake is shorter than before. In contrast, the spring slider in the high-permeability model does not change much in comparison with the reference model (i.e., the model with no fluid injection). As for the response of permeability evolution in damage zones, the low-permeability model has higher permeability changes due to higher pore pressure in the damage zones. These results are expected in cases where the fluid injection is taken in the fault core. An opposite behavior might rise if the pressure perturbation is outside the fault zone and pressure is diffusing into it, rather than out of it. In the case where the injection is outside the fault zone, the high permeability will allow the pore pressure to diffuse faster into the fault core resulting in higher pore pressure values and thus weakening it. The opposite will happen with the low permeability model.

To better estimate the pore pressure distribution after fluid injection, specific geological conditions should be considered. We acknowledge the complexity of the fault geometry and the surrounding layers. However,
in this study, we simplify the problem and focus on the influence of permeability evolution in damage zones and permeability in the country rock to understand the effect of these factors on long time scales. Furthermore, our proposed model could be incorporated into site studies to assess potential risks of wastewater injection projects and gain deeper understanding on the initiation and development on induced seismic sequences.

5.2. Effect of Healing Rate on Permeability Evolution in Scenario 2

As shown in the simulation results of scenario 2, in Figures 6 and 7, the permeability could recover to its original value during the interseismic period, however, such healing rate is based on the assumption that the temperature is $T = 250^\circ C$ and the temperature $T = 50^\circ C$ based on a reference crack lifetime of $\lambda_0 = 4000$ yrs at $T_0 = 40^\circ C$.  

Figure 9. Simulation results including slip velocity $V_t$ (compared with a reference model $V$ with no permeability evolution), pore pressure $p$, and permeability at zero effective stress $k_0$ based on scenario 2 with different healing rate. (a) assumes a faster healing rate with temperature $T = 250^\circ C$ based on a reference crack lifetime of $\lambda_0 = 400$ yrs at $T_0 = 40^\circ C$ and (b) assumes a slower healing rate with temperature $T = 50^\circ C$ based on a reference crack lifetime of $\lambda_0 = 4000$ yrs at $T_0 = 40^\circ C$. 

YANG ET AL. 10.1029/2021JB021787 14 of 17
of the newly opened cracks depends on the crack lifetime, which is described in Equation 6. Therefore, the temperature and the mineral composition of the damage zones determine the duration for newly open cracks to become fully sealed or closed.

In order to focus the discussion on the effect of the healing rate on the earthquake cycle, we simplify the complex geological structure and run scenario 2 simulations on two extreme cases, among which one case has temperature \( T = 250^\circ \text{C} \) with a reference crack lifetime of \( \lambda_0 = 400 \text{ yrs at } T_0 = 40^\circ \text{C} \), and the other case has temperature \( T = 50^\circ \text{C} \) with a reference crack lifetime of \( \lambda_0 = 4000 \text{ yrs at } T_0 = 40^\circ \text{C} \). The simulation results are shown in Figure 9. In the fast-healing-rate case (Figure 9a), we can see that the permeability decreases to its original level much faster than the results shown in Figure 7, so the pore pressure distribution does not change much through the whole simulation time and the slipping history of the permeability evolution model is not different from the reference model (i.e., model with time independent permeability). In the slow-healing-rate case (Figure 9b), we can see that the permeability does not have enough time to fully recover to its original value for the given interseismic period, and therefore keeps increasing and ultimately oscillates in a higher permeability range. The pore pressure in the slow-healing-rate case keeps decreasing and eventually oscillates in a lower pressure range relative to the simulation results shown in Figure 7. Thus, the displacement history of the spring slider also shows that the fault has been strengthened and the earthquake cycle period is increased.

In summary, if the permeability healing rate in damage zones, which depends on temperature and mineral composition, is fast enough to insure full recovery within the interseismic period, the effect on the earthquake cycle is limited. In contrast, in the case of slow healing, the earthquake period is increased. Thus, the pore pressure in the fault planes could either decrease to a lower level or stay constant even with newly opened large cracks due to dynamic ruptures. Nevertheless, the system will eventually reach a stable state where the pore pressure will stay fixed or oscillate in a narrow range. Furthermore, the temperatures in the fault zones are often controlled by a variety of factors, such as shear heating during coseismic ruptures (Rice, 2006), heat transferred by fluid infiltration (Engvik et al., 2009; Yehya & Rice, 2020), etc. While some may have a long-term effect on the healing rate of off-fault cracks and should be incorporated into the simulation framework, some just have a short-term effect (such as shear heating) which has a limited influence on the permeability evolution during long-term earthquake cycles, and may be considered when focusing on assessing the short-term permeability changes.

6. Conclusions

Our proposed modeling framework has the potential to incorporate different mechanical and chemical processes (e.g., different fluid sources, geothermal gradient, healing mechanisms) and can be applied to a wide range of scales, including induced earthquakes and subduction zone earthquakes.

The results of the numerical simulations show that the permeability evolution in fault damage zones can affect the earthquakes cycles by either delaying or accelerating the weakening of the fault through controlling the pore pressure distribution and changing the effective normal stress. Even without active pore pressure perturbation from fluid sources, the pore pressure could still change due to the evolution of the permeability in the damage zones. The dependence of the permeability on the effective normal stress, dynamic rupture, and thermally enhanced healing should be considered to better estimate the earthquake re-occurrence.

Different permeability evolution processes could result in totally different slipping history of faults. Our simulation results show the importance of incorporating the permeability evolution into the earthquake modeling, especially when assessing the long-term effect. Our study also highlights the importance of long-term monitoring of geophysical properties in fault damage zones, which might be achieved by direct measurements or seismic observations.

Data Availability Statement

The simulation results data related to this work can be accessed through the following link: https://doi.org/10.7910/DVN/P7VKZ3.
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