Simulating the evolution of fault zone structure in 2D fully dynamic seismic cycle simulations with continuum brittle damage

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1. Project objectives

Stress concentration from fault slip can cause off-fault damage by loading nearby materials beyond their yielding strength. Both short-term off-fault damage associated with earthquake rupture propagation, as evidenced by pulverized rocks [*Dor et al.*, 2006; *Rempe et al.*, 2013], and long-term fault zone growth during the interseismic period [*Childs et al.*, 2009; *Cowie and Scholz*, 1992; *Faulkner et al.*, 2011; *Lyakhovsky and Ben-Zion*, 2009] have been suggested to contribute to the formation of fault zone structure. The accumulative damage occurring over multiple timescales together contribute to the development of fault zones from immature structure to more localized mature structure [*Ben-Zion and Sammis*, 2003; *Chester et al.*, 1993; *Mitchell and Faulkner*, 2009; *Perrin et al.*, 2016].

The distribution of off-fault damage can provide key constraints on the overall energy budget of seismic cycles. The elastic strain energy accumulated over interseismic periods can be converted to both on-fault and off-fault dissipated energy as well as earthquake radiated energy during rupture. Previous dynamic rupture simulations demonstrate that coseismic off-fault damage activated by earthquake ruptures can significantly affect the overall energy budget during earthquakes [*Okubo et al.*, 2019]. On the other hand, off-fault damage associated with interseismic slip also causes partial loss of elastic strain energy available for earthquakes and influence the overall fault energy budget spanning seismic cycles.

Moreover, mature fault zones may have lower yielding strength due to either fluid overpressure [*Faulkner and Rutter*, 2001; *Sibson*, 1994; *Suppe*, 2014] or existence of gouge material with low friction [*Carpenter et al.*, 2015; *Collettini et al.*, 2009; *Lockner et al.*, 2011; *Remitti et al.*, 2015]. The former decreases the effective normal stress while the latter causes an intrinsic lower friction coefficient. The lowered yield strength can allow more energy dissipated through inelastic off-fault damage, which may in turn limit earthquake sizes and alter the locations of earthquakes over time [*Abdelmeguid et al.*, 2024]. Thus, the evolution of fault zone damage and strength over time plays an essential role in modeling seismicity distribution and energy budget in more realistic earthquake simulations.

Previous numerical simulations have successfully modeled the generation of fault zone damage through continuum brittle damage rheology [*Finzi et al.*, 2010; *Kurzon et al.*, 2019; *Lyakhovsky and Ben-Zion*, 2009; *Lyakhovsky et al.*, 2001; *Xu et al.*, 2015; *Zhao et al.*, 2024], which considers the feedback between damage generation and change of material properties [*Lyakhovsky et al.*, 1997]. Compared to pure off-fault plasticity, damage rheology outlines the evolution of fault zone structure and off-fault deformation together in a consistent way. Quasi-static cycle simulations incorporating damage rheology demonstrate the evolution from complex segmented structures to simpler fault zone structures [*Finzi et al.*, 2010]. However, the dynamic wavefield in fault zones may be critical for modeling earthquake rupture and coseismic off-fault damage given its strong modulation of fault stress [*Huang et al.*, 2014].

In this project, we developed a new computational framework to simulate seismic cycles in fully dynamic cycle simulations with continuum brittle damage [*Zhai et al.*, 2025]. Our simulations will focus on the respective contributions of earthquake rupture, postseismic slip and interseismic deformation to the generation and healing of fault zone damage. Further, we quantify how the structure and strength of fault zones influence the locations and recurrence patterns of earthquakes as well as energy budget over multiple seismic cycles.

2. Methodology

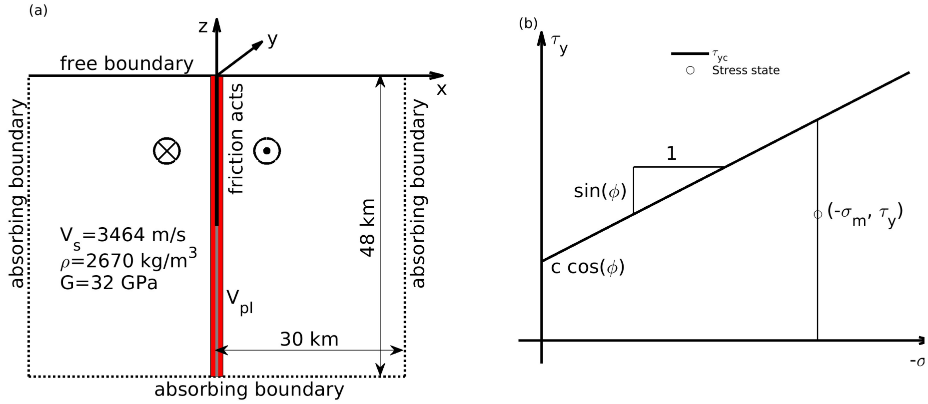

Fig. 1 (a) Model setup and (b) Drucker-Prager yield criterion for damage.

We simulate fully dynamic seismic cycles on a 2-D vertical strike-slip fault with a preexisting low rigidity zone (**Fig. 1a**). On-fault slip rate is controlled by a rate-and-state-dependent friction [*Dieterich*, 1979; *Ruina*, 1983; *Scholz*, 1998] in which the evolution of the state variable is governed by the aging law. The adjacent off-fault medium is controlled by a damage rheology framework modified for anti-plane deformation [*Zhai et al.*, 2025]. The damage of off-fault material is modeled through the generation of plastic deformation and resulting reduction in fault zone rigidity, which only occurs when the yielding condition is exceeded (**Fig. 1b**). During the postseismic period when the yielding condition is not met, fault zone rigidity also recovers and heals over time.

3. Results

3.1 Fault zone damage evolution over seismic cycles

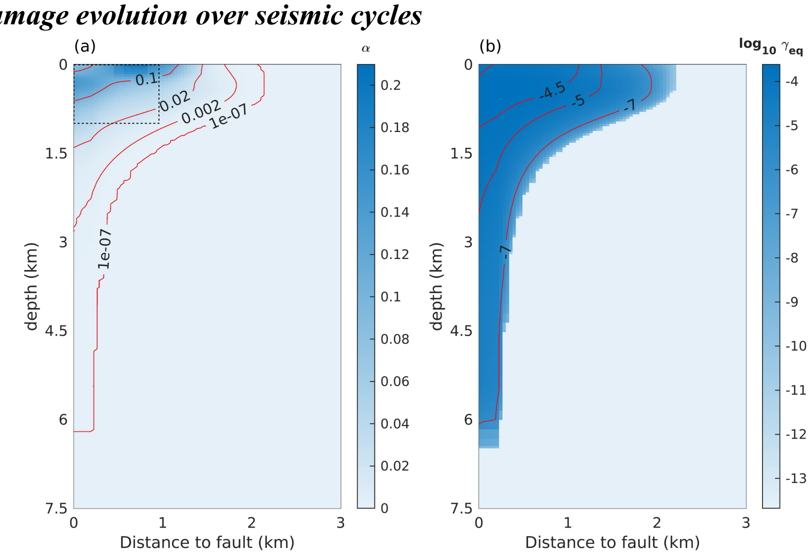

Fig. 2 Spatial distribution of (a) damage variable and (b) equivalent cumulative plastic strain ($\gamma_{eq} = \sqrt{\varepsilon^p_{ij}\varepsilon^p_{ij}}$) after the 10th event. The gray dotted line in panel (a) represents the selected area (1 km by 1 km) to calculate the average velocity drop and the corresponding shear modulus.

We observe that the accumulative reduction in fault zone rigidity and associated permanent plastic strain are also concentrated at shallow depths, forming a flower-like structure that features a diffusive area of damage surrounding a localized, intensely damaged central core [*Zhai et al., 2025*] (**Fig. 2**). We quantify the off-fault rigidity reduction by the non-dimensional damage variable α. The width of the fault zone and the absolute damage variable α both grows as cumulative fault displacement increases due to multiple earthquake ruptures. Between the first and last event, the peak post-earthquake damage variable α increases from 7% to more than 25%. Within 1 km of the fault, the damage variable at the surface (z = 0 km) exceeds 0.1, but it diminishes quickly with increasing distance from the fault, while its reduction along the dip direction is more gradual. On the other hand, permanent plastic strain persists to depths up to 6 km, with its half-width near the surface around 2 km (**Fig. 2b**). The overall thickness of the fault zone—defined by regions of positive damage variable and plastic strain—narrows with depth, becoming stable at about 200 to 300 meters near 6 km depth. Thus, the widths of this spontaneously generated damage zone range from kilometers near the surface to several hundred meters at greater depths.

We analyze the spatially averaged damage variable within a selected shallow, near-fault area, and convert the rigidity reduction to a relative drop in shear wave speed (dv/v). Our simulations reveal a coseismic velocity drop of about 1–2%, which closely matches the values observed in seismic studies [*Brenguier et al., 2008; Gassenmeier et al., 2016; Li et al., 2006; Qin et al., 2020; Qiu et al., 2019; Vidale and Li, 2003; Wang et al., 2021*]. This coseismic velocity drop recovers only partially after each earthquake, resulting in a consistent reduction spanning multiple events. Over time, this cumulative effect leads to the gradual evolution of the fault zone from an immature state to a mature, low-rigidity structure. The fault zone rigidity tends to stabilize after approximately seven events (about 1,500 years), consistent with observations that damaged fault zones eventually approach a stable, mature condition [*Mitchell and Faulkner, 2009; Savage and Brodsky, 2011*].

We additionally assess how both interseismic and coseismic damage influence the evolution of fault zone damage over time in our simulations [*Zhai et al.*, 2025]. We compare the damage produced by earthquakes with that generated during the subsequent interseismic period. Most of the coseismic damage is nearly complete within two seconds as the rupture front passes through. During the following interseismic phase, the dominant process is healing, marked by increasing seismic wave speeds. The majority of the coseismic velocity drop recovers in the first quarter of the interseismic period. The coseismic velocity drop at depths greater than 1 km almost fully recovers. The final depth profile of velocity drops at the end of the interseismic stage becomes the initial condition for the next earthquake.

3.2 Effects of fault zone yielding strength and initial rigidity

Simulations with different yielding strength and initial rigidity of fault zones further demonstrate their profound impact on seismicity evolution. Here we define the bulk internal friction of fault zone as f and the initial rigidity reduction as δG. We find high fault zone strength (f=0.6) only leads to regular characteristic events with full ruptures, while low fault zone strength (f=0.2) can result in irregular recurrence pattern and cascading earthquake sequences. When f=0.2 and $\delta G = 10\%$, various kinds of earthquake sequences including foreshock-mainshock-aftershock sequences and isolated events occur, like the observed abundant seismicity in mature fault zones. Foreshocks and aftershocks also tend to concentrate around the bottom of seismogenic zone where tectonic shear stress concentrates. We find that a larger pre-existing damage overall makes the fault zone easier to yield and contributes to more damage and cascading events, even when the fault frictional parameters are fixed. For example, the number of earthquakes for the case of 10% pre-existing rigidity reduction is 29 for an earthquake cycle of 1000 years, but it increases to 78 with 50% pre-existing rigidity reduction.

The spatial distribution of post-earthquake off-fault damage of different fault zone strength and maturity are also different. For f=0.6, damage mainly concentrates around the shallow depth and decreases as depth increases (flower structure). For f=0.2, damage can occur at depth>6 km accompanied by foreshock activities. Foreshocks coexist with the spontaneous generation of off-fault damage at depth and only rupture limited area due to significant inelastic energy dissipation. In other words, the preparation process of mainshock is a mixture of self-arrested cascading foreshock sequences and aseismic slip. The interactions between on-fault and off-fault rocks observed in our model provide another physical mechanism of foreshock evolution in addition to the heterogeneity of fault normal stress and frictional properties [*Cattania and Segall*, 2021; *Ito and Kaneko*, 2023]. Overall, low fault zone strengths can result in various kinds of earthquake sequences including foreshock-mainshock-aftershock sequences and isolated events, like the observed abundant seismicity in mature fault zones.

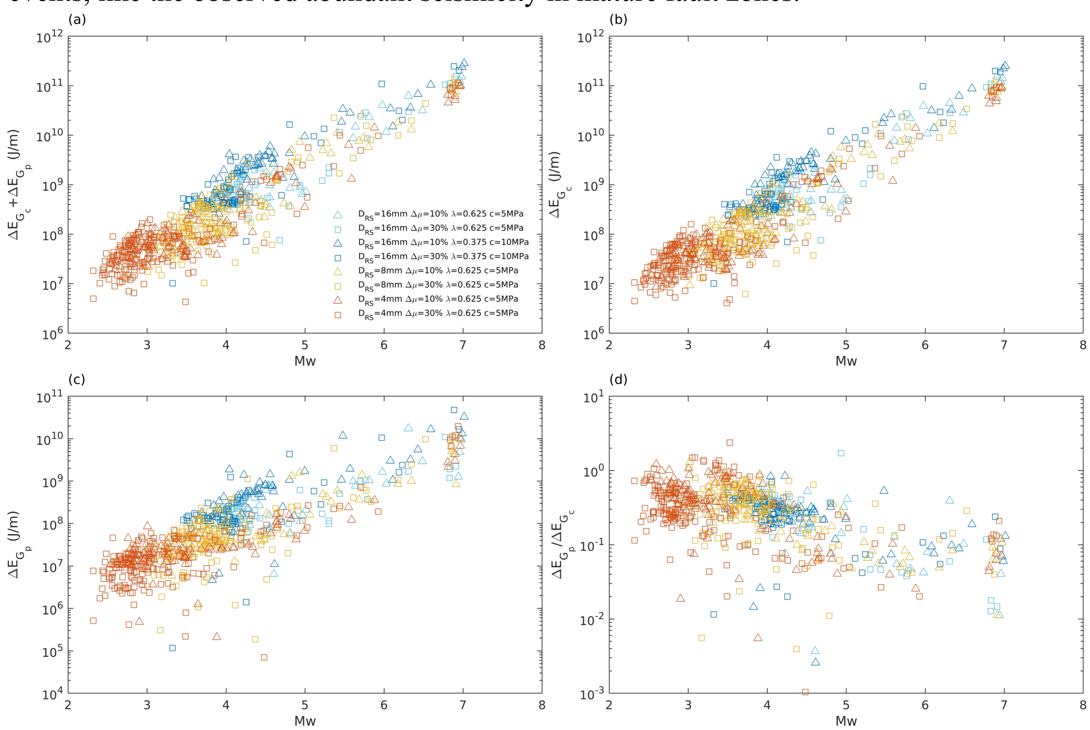

Fig. 3 The energy budget of all cascading events. (a) Total dissipated fracture energy (On-fault breakdown energy and fault zone plastic strain energy) for each earthquake. (b) On-fault breakdown energy. (c) fault zone plastic strain energy. (d) the ratio of fault zone plastic strain energy to on-fault breakdown energy.

In our simulations, the total dissipated fracture energy comprises both the on-fault breakdown energy and the off-fault plastic strain energy. We determine the on-fault breakdown energy ΔE_{G_c} for each seismic event from the fault's stress-slip evolution history. Additionally, we compute the plastic strain energy ΔE_{G_p} at each timestep to track the cumulative plastic strain over time. The net plastic strain energy caused by each seismic event is the difference between the total accumulated plastic strain energy at the start and end of the coseismic period. We find that both the on-fault breakdown energy and the plastic strain energy increase with earthquake magnitude (**Figs. 3a-c**). One interesting phenomenon is that the ratio of off-fault plastic strain energy to on-fault breakdown energy gradually decreases as earthquake magnitude increases (**Fig. 3d**). This indicates that the energy budget of small and large earthquakes is fundamentally different in our simulations. Small earthquakes dissipate a greater portion of their energy through off-fault inelastic processes. Our future goal is to quantify how the differences in earthquake dissipation impact the source properties of small and large earthquakes in our simulations and investigate whether we can observe their effects in real earthquake sequences through analyzing seismic data.

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