Fault-zone damage promotes pulse-like rupture and back-propagating fronts via quasi-static effects

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Key Points:

- Highly damaged fault zones promote pulse-like ruptures even without the dynamic effects of reflected waves.
- Slip complexity induced by fault damage involves multiple back-propagating rupture fronts.
- A new mechanism for Rapid-Tremor-Reversals observed during Episodic Tremor and Slip.

Keywords

rupture dynamics · slow earthquakes · fault zone · damaged zone · rapid-tremor-reversals

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Abstract

Damage zones are ubiquitous components of faults that may affect earthquake rupture. Simulations show that pulse-like rupture can be induced by the dynamic effect of waves reflected by sharp fault zone boundaries. Here we show that pulses can appear in a highly damaged fault zone even in the absence of reflected waves. We use quasi-static scaling arguments and quasi-dynamic earthquake cycle simulations to show that a crack turns into a pulse after the rupture has grown larger than the fault zone thickness. Accompanying the pulses, we find complex rupture patterns involving back-propagating fronts that emerge from the primary rupture front. Our model provides a mechanism for back-propagating fronts recently observed during large earthquakes. Moreover, we find that slow-slip simulations in a highly-compliant fault zone also produce back-propagating fronts, suggesting a new mechanism for the rapid-tremor-reversals observed in Cascadia and Japan.

Plain Language Summary

Damage zones are zones of fractured rock that surround faults and can influence how earthquakes propagate. Previous computer models show that damage zones promote an inchworm-like (rather than zipper-like) pattern of earthquake propagation, known as pulses. This finding has been previously attributed to the effect of seismic waves reflected at the boundaries of the damage zone. Here, we show that pulses are generated in highly-fractured damage zones independently of the reflection of seismic waves. We reach this conclusion by scaling arguments confirmed by numerical simulations of sequences of earthquakes in which we ignore the reflection of seismic waves. Moreover, our models produce an unexpected pattern of earthquake propagation: secondary rupture fronts emerge from the primary rupture front and propagate in the opposite direction. Similar back-propagating fronts have been previously observed during slow earthquakes in subduction zones and more recently during large earthquakes. Our work reveals a possible connection between an observable structural feature of faults and complicated patterns of earthquake propagation.

1 Introduction

Pulse-like rupture (hereafter referred to as pulses) is a common mode of earthquake propagation in which the duration of slip at each point of the fault, known as the rise-time, is short compared to the total rupture duration (Heaton, 1990). Pulses play a prominent role in the theory of earthquake mechanics: they can radically affect the earthquake energy balance (Nielsen & Madariaga, 2003), reduce the apparent strength of faults (Noda et al., 2009), enhance the spatial heterogeneity of earthquake slip and stress (Aagaard & Heaton, 2008), and promote complexity of seismicity manifested by a broad range of event magnitudes (Cochard & Madariaga, 1996). Yet their origin is not completely established. Several mechanisms of pulse generation have been proposed, involving healing fronts emerging from features of the friction law (Cochard & Madariaga, 1996; G. Perrin et al., 1995), from early arrest of one dimension of rupture (Day, 1982; Johnson, 1990), from fault heterogeneities (Beroza & Mikumo, 1996; Day et al., 1998) or from waves reflected in a low-velocity fault damage zone (Huang & Ampuero, 2011). The present work focuses on the generation of pulses by damaged zones.

Faults are usually embedded in a damaged zone (Fig. 1a) characterized in field observations by distributed fractures and micro-cracks (Chester & Logan, 1986; Mitchell & Faulkner, 2009; Savage & Brodsky, 2011) and in seismological and geodetic observations by reduced wave speeds or elastic modulus relative to the host rock (Y.-G. Li et al., 1990, 2002; Ben-Zion et al., 2003; Peng et al., 2003; M. Lewis et al., 2005; Y.-G. Li et al., 2006; H. Li et al., 2007; Mizuno et al., 2008; Cochran et al., 2009; M. A. Lewis & Ben-Zion, 2010; Yang & Zhu, 2010; Yang et al., 2011). Seismic imaging methods resolve fault zones of strike-slip faults as flower-structures with depth-varying thickness and damage (Ben-Zion et al., 2003; Finzi et al., 2009). Hereafter, we refer to these structures as low-velocity fault zones (LVFZ).

Dynamic rupture simulations show that the presence of a LVFZ can induce complex rupture patterns: pulses promoted by healing fronts mediated by reflected waves, oscillations of slip-rate and rupture speed, and supershear rupture at low background stress (Harris & Day, 1997; Huang & Ampuero, 2011; Huang et al., 2014, 2016). Recent earthquake cycle simulations show that the generation of pulses by a LVFZ is persistent across multiple earthquake cycles, both in fully-dynamic (Thakur et al., 2020) and quasi-dynamic simulations (Idini & Ampuero, 2017). The mechanism of pulse generation by a LVFZ has been previously attributed to the dynamic effect of waves reflected at the boundary of the LVFZ, which tend to unload the fault and promote slip arrest (Huang & Ampuero, 2011; Thakur et al., 2020). However, LVFZ quasi-dynamic simulations do not include these reflected waves. Here, we explain how pulses can be promoted in LVFZs by a quasi-static mechanism.

The present work is further motivated by recent evidence of complex rupture patterns in earthquakes and tectonic tremors, in particular back-propagating fronts. While the inherent complexity of large earthquakes is abundantly highlighted by modern seismological observations (Meng et al., 2012; Ross et al., 2019), reports of secondary rupture fronts propagating in the direction opposite to the main front (i.e., towards the hypocenter) are becoming increasingly clear and robust (Beroza & Spudich, 1988; Meng et al., 2011; Uchide et al., 2013; Hicks et al., 2020; Vallée et al., 2020). Back-propagating fronts have also been identified during slow slip events (SSE) in Cascadia and Japan, appearing as tremor swarms known as Rapid Tremor Reversals (RTR) which migrate at fast speed in the direction opposite to the propagation of the large-scale slow slip (Houston et al., 2011).

Here, we show that pulses can be generated by a highly-damaged LVFZ, even without the dynamic effects of reflected waves. We follow two complementary approaches: static rupture scaling arguments (Section 2) and quasi-dynamic earthquake cycle simulations (Section 3). Our simulations also reveal that the quasi-static effects of a highly-damaged LVFZ are sufficient to generate back-propagating fronts.

2 Scaling arguments for quasi-static pulse generation

We consider a simple, tabular LVFZ model defined by a finite fault of length L bisecting a homogeneous low-rigidity layer, the damage zone, embedded in an intact medium (Fig. 1). The LVFZ is specified by its half-thickness h and its damage level Δ defined by:

$$\mu_d = (1 - \Delta)\mu \tag{1}$$

where μ_d and μ are the shear moduli of the LVFZ and intact medium, respectively. We consider anti-plane deformation. The model converges to two different homogeneous end-member models, depending on the fault zone thickness. When h/L is very small, the model approaches a homogeneous intact medium with shear modulus μ. When h/L is very large, the model tends to a homogeneous damaged medium with shear modulus $(1 - \Delta)\mu$.

Key effects of a LVFZ on rupture propagation are highlighted by analyzing the limiting case of a highly damaged fault zone ($\Delta \to 1$), which is asymptotically equivalent to the case of a rigid medium surrounding an elastic fault zone considered by (Horowitz & Ruina, 1989). We consider a rupture growing quasi-statically with prescribed uniform stress drop $\Delta\tau$ and increasing rupture half-length $r(t)$. The fault-zone thickness h is fixed and, for illustrative purposes, we set $\Delta = 0.99$. The resulting slip profiles (Fig. 1c) are computed by solving numerically a static problem in which we account for static stress interactions modified by the presence of the damaged layer, as described in Text S2. The shape of the slip profile is indicative of the style of rupture: crack-like ruptures show an

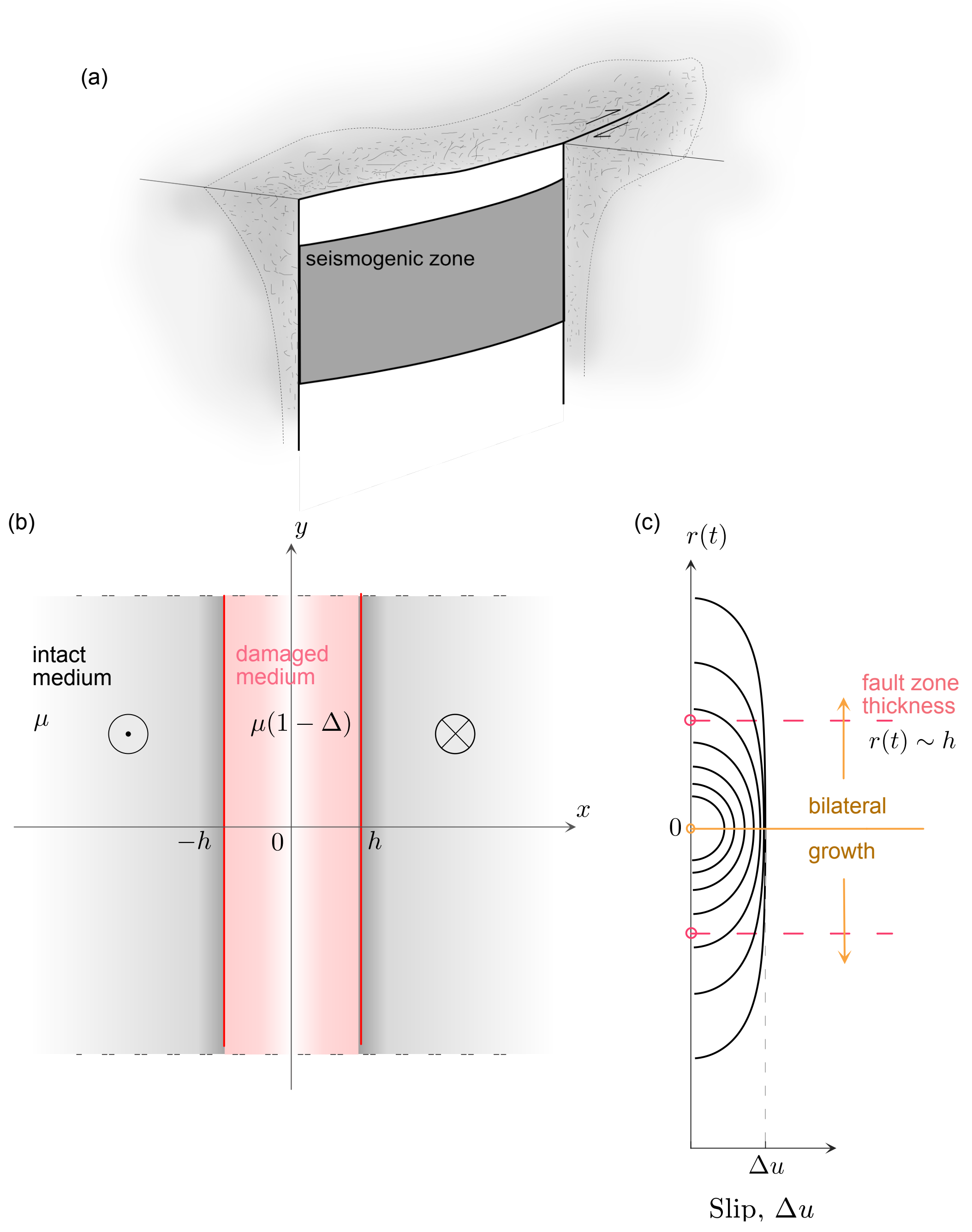

Figure 1. (a) Schematic representation of a fault zone. (b) Conceptualization of a fault zone as a simple tabular Low Velocity Fault Zone (LVFZ) model. The damaged and intact media have constant shear modulus, $(1 - \Delta)\mu$ and μ, respectively. (c) Quasi-static rupture growth with uniform stress drop in a LVFZ, showing a transition from crack-like (elliptical) to pulse-like (flat) slip profiles when the rupture length exceeds the LVFZ thickness. The static slip profiles are computed numerically for $\Delta = 0.99$ by the method described in Text S2.

elliptical slip profile whereas (steady-state) pulses have a flat slip profile (Gabriel et al., 2012). While the rupture is small ($r(t) \ll h$), it only interacts with the damaged zone and therefore has a crack-like slip profile, as in a uniformly damaged infinite medium. Its slip grows proportional to rupture length as $\Delta u(t) \sim \frac{\Delta\tau}{2\mu(1-\Delta)} r(t)$. As the rupture grows large ($r(t) \gg h$), it interacts with a thin elastic slab of thickness h and develops a pulse-like slip profile. Its slip reaches a value independent of rupture length, $\Delta u \sim \frac{\Delta\tau}{\mu(1-\Delta)} h$, as expected in a thin slab problem. Connecting these two rupture stages together, a growing rupture with constant stress drop in a highly-damaged LVFZ will initiate as a crack-like rupture and later transition into a pulse. The transition is characterized by saturation of slip caused by the LVFZ once the rupture grows larger than $2h$.

The above picture of crack-to-pulse transition provides insight into what controls rise-time in a damaged fault zone in the absence of wave reflection effects. The rise-time at the hypocenter is the time required for the appearance of a healing front. This time corresponds kinematically to the emergence of pulses, which is approximately the time required for the size of the initial crack to grow up to $r(t) = h$. Assuming a constant rupture speed v_r, the size of the rupture is $r(t) \sim v_r t$, hence the rise time at the hypocenter roughly follows:

$$t \sim \frac{h}{v_r} \tag{2}$$

This estimation of rise-time is valid at other locations beyond the hypocenter assuming that the propagation speed of the healing front is close to the rupture speed. Because rise-time can be shorter away from the hypocenter (Huang & Ampuero, 2011), Eq. (2) should be taken as an upper bound. The resulting upper bound for the pulse width, defined as the distance between the position of the rupture front and the healing front, is:

$$l \sim v_r t \sim h \tag{3}$$

The foregoing simplified analysis predicts the emergence of pulses from static effects alone, independently of the presence of reflected waves in the LVFZ.

3 Pulses and back-propagating fronts in quasi-dynamic multi-cycle models

We conduct quasi-dynamic earthquake cycle simulations under rate-and-state friction (Text S1 for methods), covering a wide range of values of LVFZ thickness and damage. Our simulations do not include dynamical effects from reflected waves. Each simulation produces a history of seismic activity, including earthquakes with multiple sizes (Fig. S1). The largest earthquakes in one simulation span the whole seismogenic length L_{vw} (Fig. S2) and are labeled as characteristic events. In a given fault model, characteristic events have the same magnitude but may show different rupture patterns. We define an earthquake cycle as the period between two characteristic events. In some fault models, simulations show a variable duration of the earthquake cycle. We only consider results in characteristic events after a spin-up period of several initial cycles, avoiding a dependence of our results on the arbitrarily-prescribed initial conditions.

Complex slip patterns appear in characteristic events when damage is high ($\Delta > 0.7$) and the fault zone is thin compared to the length of the seismogenic zone ($2h < L_{vw}$). Two signatures characterize the slip complexity: the promotion of pulses (Fig. 2a) and the re-rupture of previously healed fault segments during the same event (Fig. 2b,e).

Pulses are defined here by a drastic reduction of slip rate ($V < 1$ cm/s) at a short distance behind the rupture front, leading to a short rise-time. We observe a systematic reduction of the average rise-time over a wide range of LVFZ thickness and high damage values (Fig. 2a). Short rise-times occur roughly within the range of LVFZ parameters that produce flat slip profiles in the static rupture models computed in Section 2

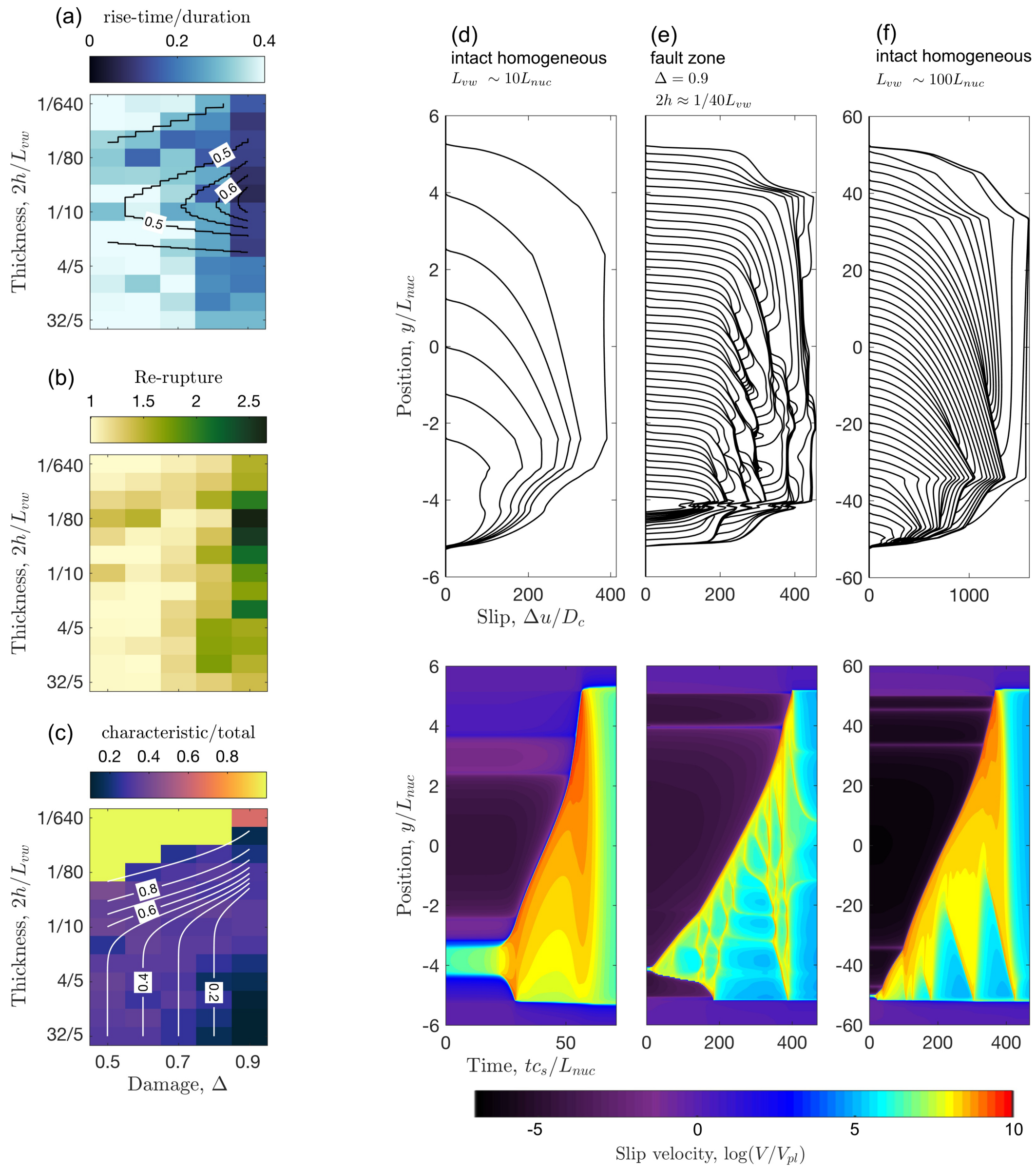

Figure 2. Properties of ruptures and seismicity in fault-zone models after multiple earthquake cycles and spatiotemporal evolution of slip and slip velocity in the characteristic event of earthquake cycle models . (a) Average rise-time normalized by the total rupture duration, (b) average number of rupture fronts ($V > 1$ cm/s) during an event, and (c) number of characteristic events over the total number of events as a function of damage level Δ and fault-zone thickness $2h$ normalized by the size of the velocity-weakening fault segment L_{vw}. The rise-time is defined here as the duration of slip rate exceeding 1 cm/s. Black contour lines in (a) are a semi-analytical prediction of the flatness of the slip profile in a constant stress drop model (Text S2). The slip profiles are obtained with the same method used in Fig. 1c. Flatness is the fraction of the fault length where slip is roughly constant, at most 20% lower than the maximum slip in the slip profile. The white contours in (c) show the estimated reduction of the nucleation length due to the LVFZ (contours of L_{nuc} in LVFZ normalized by its value in a homogeneous intact medium). (d) Spatiotemporal evolution of slip and slip velocity in the characteristic event of an intact homogeneous medium, (e) a LVFZ with $\Delta = 0.9$ and $2h \approx L_{vw}/40$, and (f) an intact homogeneous medium with ten times smaller nucleation length than (d).

(Fig. 2a), consistent with the kinematic implications we drew from the static crack analysis.

The re-rupture of previously healed fault segments (Fig. 2b) is characterized by the emergence of secondary fronts propagating in the opposite direction to the main rupture front (Fig. 2e and Fig. S3). These back-propagating fronts have a short rise-time and can re-rupture multiple times the same fault segment. Models with seismogenic zones that are much larger than the nucleation size ($L_{vw} \gg L_{nuc}$; Text S1) promote back-propagating fronts without requiring a LVFZ, but their rise-time is longer and their number of re-ruptures is small (Fig. 2f with $L_{vw} \sim 100L_{nuc}$).

In addition to characteristic events with complex slip patterns, events comprising a wide range of sizes develop in thick and highly damaged fault zones (Fig. 2c), where small events partially break the seismogenic zone from the edges (Fig. S1). Small, non-characteristic events are known to emerge in rate-and-state friction models in homogeneous media with seismogenic zones much larger than their nucleation length L_{nuc} (Cattania, 2019; Barbot, 2019). The nucleation length is the smallest size of a slip patch that can accelerate to instability (Rubin & Ampuero, 2005). In a homogeneous medium it is proportional to the shear modulus, and in a damaged zone to a reduced, effective shear modulus that depends on h and Δ (Text S1). The LVFZ thickness and damage values promoting variable event magnitudes in our models are well explained by the increase in the L_{vw}/L_{nuc} ratio due to the reduction in L_{nuc} induced by the LVFZ (Fig. 2c). The smallest nucleation length is achieved in models with $\Delta = 0.9$ and $2h > L_{vw}$, which have $L_{vw} \sim 100L_{nuc}$.

The rupture speed in our homogeneous medium model (Fig. 2d) corresponds to $V_{rup} \sim$ 1 km/s, a typical value in seismological observations. In contrast, a highly-damaged fault zone promotes a reduction in the rupture speed $V^d_{rup}/V_{rup} \propto (1-\Delta)$, compatible with theoretical quasi-static predictions of rupture speed (Ampuero & Rubin, 2008) but slower than most seismological observations. The non-dimensional units in Fig. 2 can be converted into real scales depending on the assumed value of the characteristic slip distance of rate-and-state friction, D_c; examples of dimensional scales are given in Table S1 for $D_c = 2$ mm.

4 Discussion

4.1 Short-range stress transfer and the origin of pulses in a LVFZ

Models with nearest-neighbour stress transfer, such as the Burridge-Knopoff (BK) model (Burridge & Knopoff, 1967), have been often used as a mechanical analog to earthquake rupture and are capable of promoting pulses in the continuum limit (Erickson et al., 2011; Brener et al., 2018). In a BK model, a chain of sliders connected by springs is loaded by a uniform displacement applied to a loading spring (Burridge & Knopoff, 1967). In a uniform stress drop rupture, the BK model produces the flat static slip profile characteristic of pulses when the loading stiffness is much higher than the static stress transfer due to the relative motion of sliders (Text S3). Under our current model parameters (Table S2), ruptures propagate as pulses both in a nearest-neighbour model (Fig. 3a) and in a fault-zone model with large damage, $\Delta = 0.9$ (Fig. 2e). Here we show that the emergence of pulses in a LVFZ can be related to stress interactions approaching the nearest-neighbour regime across a wide range of slip wavelengths.

The static stress transfer in a fault-zone model due to spatially-harmonic slip with wavelength k and unit amplitude is (Text S2, Fig. S4):

$$\mathcal{K}(k) = \frac{1}{2}\mu(1-\Delta)|k| \coth\left(h|k| + \operatorname{atanh}(1-\Delta)\right) \quad (4)$$

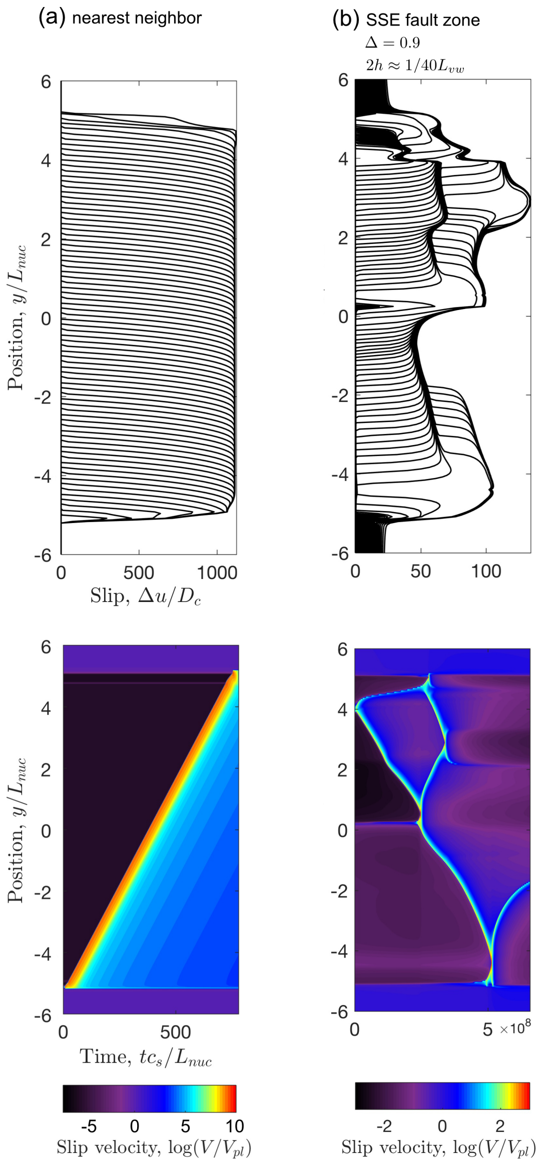

Figure 3. Spatiotemporal evolution of slip and slip rate in the characteristic event of earthquake cycle models assuming (a) a nearest-neighbor model with $\Delta = 0.99$ and $2h = L_{vw}/25$ and (b) a slow-slip model in a LVFZ model with $\Delta = 0.9$ and $2h \approx L_{vw}/40$ and a modified friction law with velocity-strengthening at high velocities. Axes are normalized following the convention in Fig. 2.

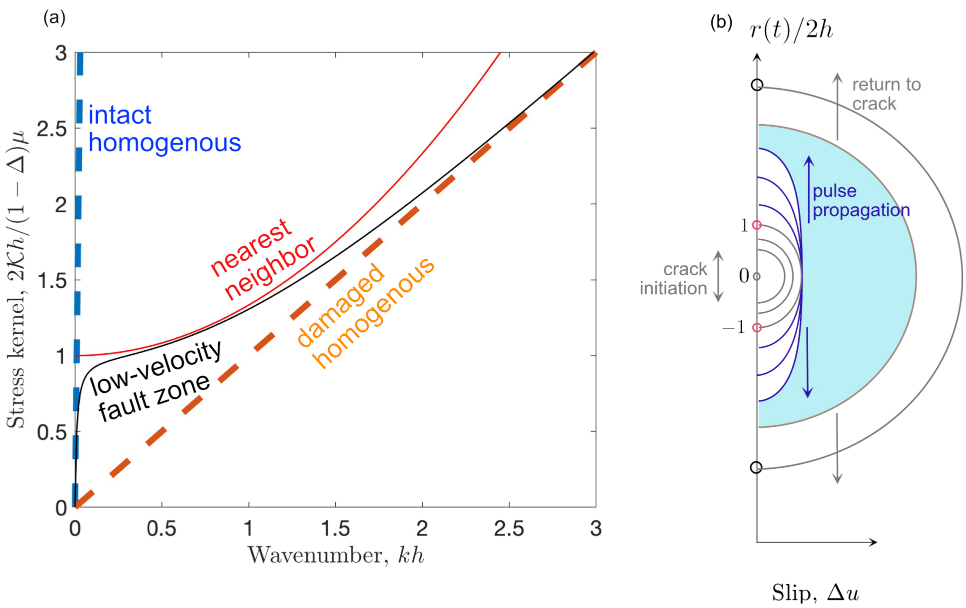

Figure 4. Nearest-neighbor stress transfer and promotion of slip complexity. (a) The static stress transfer kernel of a LVFZ (Eq. 4) with $\Delta = 0.99$ (black) in Fourier domain, as a function of the normalized wavenumber kh of slip, and its nearest-neighbor approximation (red) (Text S3). Also shown are the asymptotic limits of a homogeneous intact medium (blue dashed) ($\mathcal{K} = \mu|k|/2$) and homogeneous damaged medium (orange dashed) ($\mathcal{K} = \mu_d|k|/2$). The exaggerated level of damage $\Delta = 0.99$ represents the asymptotic limit of a LVFZ as damage increases. (b) Conceptual interpretation of the emergence of secondary pulses. Re-rupturing is necessary to fill the slip deficit (cyan) between a pulse at intermediate rupture length ($r(t) > 2h$, purple curves) and a crack appearing at much larger lengths ($r(t) \gg 2h$, gray curves).

Asymptotic analysis (Fig. 4a, Text S3) shows that at low k the stress transfer in a LVFZ tends to that of an intact homogeneous medium, whereas at high k it tends to that of a damaged homogeneous medium. In an intermediate range of wavelengths, the stress transfer is approximately nearest-neighbour. As Δ increases, the relative bandwidth of the nearest-neighbour regime broadens (Fig. S8), and the short rise-time observed in the nearest-neighbor model (Fig. 3a) appears in the LVFZ model as well. In other words, increasing the LVFZ damage level extends the range of slip length scales where pulses can exist. When h is small ($h \ll \sqrt{3}L_{vw}$), a LVFZ model within the nearest-neighbour regime produces uniform stress drop ruptures with a slip profile that is flat and has an average slip $\approx 2h\Delta\tau/(1-\Delta)\mu$ (Text S3).

The limiting case where $\Delta \to 1$, analyzed in Section 2, represents an elastic layer of thickness $2h$ bounded by an infinitely rigid medium (Horowitz & Ruina, 1989). Stress interactions in that case are nearest-neighbour at wavelengths larger than $\sim 2\pi h$ (Fig. S8). Such model is completely nearest-neighbour if the process zone size, the smallest characteristic length scale of slip, is larger than $\sim 2\pi h$.

4.2 Origin of back-propagating fronts

Highlighted in our work as a manifestation of rupture complexity, back-propagating fronts owe part of their relevance to recent earthquake observations. A recent report from a M7.1 oceanic transform earthquake features a "boomerang earthquake" slip pattern (Hicks et al., 2020) that resembles the structure of back-propagating fronts shown in our models. Seismic observations indicate that LVFZs extend throughout the seismogenic zone in oceanic transform faults (Roland et al., 2012), enhancing the relevance of our model to explain the "boomerang earthquake" slip pattern. In a different tectonic setting, a back-propagating front appears during a recently reported M8 intermediate-depth earthquake (Vallée et al., 2020). Both observations are independently supported by teleseismic back-projection imaging and finite source inversion, suggesting the ubiquity of back-propagating fronts to different tectonic environments.

The static solutions introduced in Section 2 provide insight on the origin of multiple back-propagating fronts. Relying on an idealized situation where the only deformable medium is within the LVFZ, we showed the emergence of a transition from a crack into a pulse when the rupture size exceeds $2h$. In reality the medium outside the LVFZ is deformable as well. As the rupture continues growing to sizes much larger than $2h$, stress increasingly transfers through the outer medium. Eventually, the influence of the LVFZ becomes irrelevant to the propagation of the rupture. At this point, the static analysis predicts a second, reverse transition from pulse-like behavior to the crack-like behavior of an intact homogeneous medium (Fig. 4b). Beyond this transition, slip increases in regions that were previously healed. Therefore, slip reactivation is required there, leading to secondary rupture fronts.

We expect re-ruptures to initiate where stresses are the highest, which is near the primary rupture front, thus the ensuing secondary rupture fronts have to propagate backwards. Furthermore, because these secondary ruptures start small, they need to go through a pulse-like phase. In summary, in the presence of a LVFZ, back-propagating pulses are necessary to complete the slip budget of a very large rupture, filling the slip gap between intermediate-size pulses and large-size cracks.

4.3 A mechanism for Rapid Tremor Reversals

While observations of back-propagating fronts during earthquakes are challenging and still incipient, slow slip and tremor phenomena offer a unique and systematic opportunity to observe complex slip patterns in slow motion. The back-propagating fronts identified in Fig. 2e suggest that a highly-compliant LVFZ can provide a mechanism for

Rapid Tremor Reversals (RTRs) observed in Cascadia and Japan during slow-slip events (Houston et al., 2011). Seismological observations suggest that subduction megathrusts are surrounded by low-velocity zones (Nedimović et al., 2003; Audet & Schaeffer, 2018) that are several kilometers thick near the region where tremor activity concentrates (Calvert et al., 2020). Instead of damaged rock, low-velocity zones in subduction zones mostly relate to layers of subducted material containing pressurized fluids. Previous models of RTR rely on frictional heterogeneities (Luo & Ampuero, 2017; Luo & Liu, 2019), pore fluid pressure waves (Cruz-Atienza et al., 2018), or external transient forcings such as tides (Hawthorne & Rubin, 2013b). Our models show RTR-like patterns emerging from a different mechanism: the quasi-static stress transfer of a LVFZ. Due to the ubiquity of LVFZ to both regular earthquakes and slow slip events, our model supports the idea that detailed observations of slow slip phenomena contribute to understand earthquakes in general (Michel et al., 2019).

(Nedimović et al., 2003; Audet & Schaeffer, 2018) (Calvert et al., 2020).

Our simulations show that back-propagating fronts also occur in slow slip models with a LVFZ (Fig. 3b). Introducing strengthening at high slip rate is a known approach to model slow-slip events (Hawthorne & Rubin, 2013a). We added a linear velocity-strengthening term into the friction law (i.e., the fault strengthens proportionally to V), which is stronger than the logarithmic strengthening term of the conventional rate-and-state friction (Text S1). We chose a velocity-strengthening coefficient 10^6 times larger than the radiation damping coefficient. Our results indicate that back-propagating fronts emerge during slow-slip events in a LVFZ model with the modified friction, although they are less vigorous than those observed in our fast-rupture results (Fig. 3). Slow-slip events only show pulse-like behavior and back-propagating fronts in the presence of a LVFZ (Fig. S5). As slow-slip models are insensitive to dynamical effects, our results confirm that back-propagating fronts emerge from quasi-static LVFZ effects alone. The SSE propagation speed in our model is ~ 5 m/day, about 1000 times lower than SSE propagation speeds observed in Cascadia, which range from 7 to 15 km/day (Houston et al., 2011). Further work is required to examine how low-velocity zones quantitatively affect tremor migration patterns in more detailed slow-slip models.

The damage level observed in strike-slip faults ranges from 0.45 to 0.85 and the fault zone thickness from 80 to 1500 m, with typical values $\Delta \sim 0.65$ and $2h \sim 200$ m (Fig. S6). The most damaged fault-zone structures reach $\Delta \sim 0.85$ (H. Li et al., 2007; Yang & Zhu, 2010), which is close to the minimum value required by our model to show significant slip complexity (Fig. 2a,b). For $\Delta \sim 0.85$ and a reasonable fault-zone thickness $2h$ from 100 m to 1 km, the rupture length required to develop pulses and back-propagating fronts must be larger than 2 to 20 km (Fig. 2a,b). It is likely then that the quasi-static LVFZ effects described here do not operate during very small slow slip events. The properties of fault zones where RTRs are observed are harder to be resolved compared to crustal faults due to the larger depths involved. Dimensions of fault zones in subduction environments have been inferred from observations in exhumed subduction zones (Rowe et al., 2013) but their elastic properties remain poorly constrained. Receiver functions suggest that the v_p/v_s ratio may increase over $\sim 75\%$ due to over-pressurization of fluids within the several-km-thick low-velocity zone that surrounds regions where tremors are generated (Audet & Schaeffer, 2018; Calvert et al., 2020).

4.4 Potential model limitations

Further research is warranted to investigate whether the effects observed in our idealized fault zone model remain after releasing some of the simplifying assumptions, in particular the quasi-dynamic approximation and the 2D tabular LVFZ geometry.

Quasi-dynamic simulations in the absence of a LVFZ qualitatively agree with fully-dynamic simulations under a conventional Dieterich-Ruina friction law (Thomas et al., 2014). However, dynamic simulations that include a LVFZ produce a range of fault zone waves, including reflected, trapped and head waves (Huang & Ampuero, 2011; Huang et al., 2014), which can perturb the dynamic stress on the fault and interfere with the quasi-static mechanism highlighted in the present work. Preliminary results suggest that dynamic effects modulate, but do not obliterate the quasi-static effects reported here (Flores-Cuba et al., 2020). Similarly, in previous dynamic single-rupture simulations (Huang et al., 2014) dynamic LVFZ wave effects modulate, but do not obliterate the generation of pulses by another mechanism, enhanced velocity-weakening friction. An important open question is whether the dynamic effects of fault zone waves allow the slip complexity revealed here to operate over a broader range of LVFZ property values, including the lower, commonly observed levels of fault-zone damage.

The direction of slip is not important in the context of our quasi-dynamic model. Our anti-plane results can be transferred to in-plane slip by replacing μ with $\mu/(1-\nu)$, where ν is Poisson's ratio. However, in-plane dynamical models can promote additional slip complexity, for instance transitions to super-shear rupture speed which are relevant for the interpretation of past earthquakes (Huang et al., 2016; Oral et al., 2020).

The 3D structure of damage zones observed in the field is more complicated than a simple 2D tabular region, usually displaying flower structures with wider thickness at shallower depth (Finzi et al., 2009; Mitchell & Faulkner, 2009; Savage & Brodsky, 2011). Moreover, LVFZ properties are not uniform along strike as the fault-zone thickness varies with along-strike changes in fault geometry and the total amount of slip locally accumulated over time (Mitchell & Faulkner, 2009; C. Perrin et al., 2016; Ampuero & Mao, 2017). How such systematic variations of LVFZ properties affect the rupture features highlighted here warrants further study. We expect that the promotion by LVFZ of pulses and back-propagating fronts reported in our 2D simulations should also appear in 3D simulations, as the static transfer mechanism is approximately the same (similar to Eq. 4 with k replaced by the modulus of the wavenumber vector).

The quasi-static pulse-generation mechanism revealed here should persist in a LVFZ without the sharp elasticity contrasts of a simple tabular damage zone, in contrast to the dynamic mechanism of pulse-generation by reflected waves (Huang et al., 2014). In fact, the static stress transfer in a model with exponential decay of damage as a function of distance from the fault (Ampuero et al., 2002) has the same essential features as in our tabular model (Eq. 4), in particular the same asymptotic behaviors highlighted in Fig. 4.

5 Conclusions

Our analytical arguments and simulation results show that rupture pulses emerge and persist across multiple earthquake cycles via quasi-static effects in a fault surrounded by a highly-damaged fault zone, independently of the dynamic effects induced by fault-zone-reflected waves. We develop a formal analogy between a fault zone model and a nearest-neighbor (Burridge-Knopoff) model that explains the emergence of pulses. Nearest-neighbor models are known to produce pulses and, within a certain range of length scales, the stress transfer in a damaged fault zone is approximately nearest-neighbor. Our results suggest that the earthquake rise-time should be proportional to fault zone thickness divided by rupture speed in highly-damaged faults.

We also showed that fault-zone effects can produce complex slip patterns, including back-propagating fronts that re-rupture previously healed fault segments. Such back-propagating fronts have been most recently observed in large earthquakes. The back-propagating fronts in our slow-slip models with highly-damaged fault zones are also analogous to rapid tremor reversals observed in Cascadia and Japan.

Overall, quasi-static fault-zone effects provide a simple mechanism to promote and sustain earthquake complexity, and a mechanical link between structural fault properties and seismicity. Our results further motivate the quest for higher temporal and spatial resolution in earthquake source studies. The systematic exploration of model parameters contained in our results provide targets for laboratory experiments aimed at understanding the interactions between rupture propagation and heterogeneous media.

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Author contributions

Both authors contributed to the writing of the manuscript and the interpretation of the numerical results. B.I. developed the scaling argument, performed the numerical simulations, and prepared the figures. J.-P. A. designed the study, developed the expressions for the spectral kernel, the static crack numerical solutions and the asymptotic analysis connecting the BK and LVFZ models.

Data availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Code availability

The Quasi-DYNamic earthquake simulator (QDYN) (Luo et al., 2017) used to compute our numerical models of earthquake cycles is available at github.com/ydluo/qdyn. QDYN is freely available for academic research purposes and licensed by GNU General Public License, version 3.

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