

Spontaneous segmentation of slow slip events on a homogeneous planar fault

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1 **Title page:**

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11

Abstract

Slow slip events (SSEs) are transient aseismic fault slip events that often display segmentation along strike. While fault segmentation is commonly attributed to physical heterogeneities, numerical studies have shown that segmentation can also occur on homogeneous planar faults. In this study, we investigate the dynamics of SSEs on a homogeneous planar fault with velocity-weakening (VW) properties, focusing on the influence of the surrounding velocity-strengthening (VS) region. Based on numerical simulations, we reveal that the effective normal stress in the VS region (σ_{VS}) alters the slip stability in the VW region in a non-monotonic manner. σ_{VS} controls the propagation of SSEs into the VS region: under low σ_{VS} , the rupture expands into the VS region, resulting in synchronous slip, whereas under high σ_{VS} , the SSE is confined within the VW region, triggering afterslip in the VS region. This behavior is successfully captured by a simplified two-degree-of-freedom (2DOF) spring-slider model, and the non-monotonic change of the stability in the VW region with respect to σ_{VS} is understood from linear stability analysis of the 2DOF model. σ_{VS} also drives the change in SSE patterns. By systematically varying σ_{VS} , we identify three distinct types of SSEs: periodic, quasi-

periodic, and chaotic types, occurring in the VW region even with identical frictional properties. The low σ_{VS} regime tends to produce periodic SSEs with spatiotemporally regular segmentation, while the high σ_{VS} regime is characterized by chaotic SSEs exhibiting frequently varying segment sizes and boundaries. Quasi-periodic SSEs are regarded as a transition between the two. All types of SSEs spontaneously segment without imposing heterogeneities. We demonstrate, through linear stability analysis of the continuum fault model, that differences in slip patterns are attributed to the spatial scale of the dominant unstable linearized perturbation. While the diversity of SSE patterns has been reported in previous studies, this study identifies the condition and the mechanism that control the slip patterns.

Keywords

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44 Diversity of the SSE pattern,

45 Linear stability analysis

46

47 **Main Text**

48 **1 Introduction**

49 Analyses of crustal deformation data from geodetic observations have revealed the
50 occurrence of slow slip events (SSEs) on plate interfaces worldwide (Schwartz and
51 Rokosky 2007). SSEs are considered unstable slip phenomena, similar to ordinary
52 earthquakes but with much lower slip velocity. Deep SSEs are distributed along strike in
53 the deeper extension of the seismogenic zone (Obara and Kato 2016; Schwartz and
54 Rokosky 2007). The depth-limited occurrence has been considered due to depth-
55 dependent frictional properties (e.g., Blanpied et al. 1995; Marone 1998) and the
56 reduction in effective normal stress due to high pore-fluid pressure (e.g., Kodaira et al.
57 2004; Audet and Schwartz 2013). The deep SSEs are widely modeled using the
58 laboratory-derived rate- and state-friction (RSF) law (Dieterich 1979; Ruina 1983),
59 assuming velocity-weakening friction and low effective normal stress (e.g., Liu and Rice
60 2007). Such slow instability is thought to arise when the fault dimension is comparable
61 to the critical nucleation size, representing a transitional state between stable and unstable
62 slip.

The deep SSEs typically occur in multiple segments separated along strike and repeat at roughly the same locations (Nankai: Takagi et al. 2019; Cascadia: Michel et al. 2019; Hikurangi: Wallace 2020). This along-strike segmentation has commonly been attributed to physical heterogeneities along the fault strike, such as frictional properties, effective normal stress, and three-dimensional fault geometry. Previous numerical studies have adopted this assumption to reproduce SSEs on persistent segments (e.g., Matsuzawa et al. 2013; Li et al. 2018; Perez-Silva et al. 2022).

However, numerical simulations indicate that SSEs on homogeneous planar faults can also separate into multiple segments when the fault is elongated along strike (e.g., Liu 2014; Li et al. 2018; Arnulf et al. 2021). Unlike heterogeneous faults, the boundaries of these segments are often temporary rather than fixed. Dal Zilio et al. (2020) modeled a homogeneous SSE fault elongated along strike and showed that various sizes of SSEs occur on the same fault, exhibiting chaotic slip behavior and pulse-like slip propagation (Kaveh et al. 2025). In contrast, Ohata (2023), using a similar homogeneous setup, observed spatiotemporally regular SSEs on persistent segments similar to some observations such as in Nankai. These studies demonstrate the diversity in SSE patterns

on homogeneous faults elongated along strike; some models exhibit chaotic, migrating segmentation, while others show regular, fixed segmentation. It remains unclear what conditions control this difference between chaotic and regular behaviors.

In this study, we aim to identify the conditions that control the slip behavior on a homogeneous planar SSE fault. We focus on a factor that has been overlooked in previous studies: the condition outside the SSE region. Specifically, we model a velocity-weakening fault surrounded by a velocity-strengthening region and demonstrate that the frictional properties of this surrounding region strongly influence the dynamics of SSEs. Note that we do not intend to reproduce the SSE observed in specific areas, but to elucidate the fundamental conditions that control the slip pattern.

This paper is structured as follows. In Section 2, we describe the model setting and the governing equations. In Section 3, we present the simulation results, demonstrating the spontaneous segmentation process and classifying the SSE patterns into three types (periodic, quasi-periodic, and chaotic). We also examine the diversity in the number of segments governed by initial conditions. Finally, in Section 4, we discuss the physical mechanisms underlying these behaviors by employing linear stability

95 analysis.

96

97 **2. Model**

98 *2.1 Fault model and simulation procedure*

99 In this study, we simulate the slip on a rectangular planar fault embedded in an infinite,
100 homogeneous elastic medium (Figure 1). The elastic properties are specified as a shear
101 modulus $G = 30$ GPa, Poisson's ratio $\nu = 0.25$, and S-wave velocity $c = 3.5$ km/s. We set
102 the XY-plane on the fault and the X-axis along the strike direction. The fault spans $L_{VS} =$
103 360 km and $W_{VS} = 100$ km in the X- and Y- directions, respectively. The fault is loaded
104 in the direction of the Y-axis with a long-term slip velocity of $V_{pl} = 60$ mm/yr.

105 We discretize the fault into N_c subfaults with a cell size of $1 \text{ km} \times 1 \text{ km}$ and employ
106 the boundary integral element method (BIEM) to calculate the slip evolution on the fault.
107 This grid resolution is sufficient to resolve the cohesive zone size required for stable
108 simulation; we confirmed this by performing a resolution test with a $0.25 \text{ km} \times 0.25 \text{ km}$
109 mesh. The slip and stress are uniform in each subfault, and only the Y-components are
110 considered. The shear stress τ_i on cell i ($i = 1, \dots, N_c$) at time t is given by

$$\tau_i(t) = \sum_{j=1}^{N_c} K_{ij}(u_j(t) - V_{pl}t) - \frac{G}{2c} V_i(t). \quad (1)$$

Here, u_j and V_i are the slip amount at cell j and the slip velocity at cell i , respectively. K_{ij} is the slip response function, representing the shear stress change at cell i due to unit slip on cell j , computed following Okada (1992). As pointed out by Bradley and Segall (2014), the original Okada code contains numerical errors arising from cancellation, leading to asymmetric solutions even in completely symmetric problems. To avoid this problem, we employ a modified version of the code proposed by Bradley and Segall (2014). The second term on the right-hand side is known as the radiation damping term, introduced via the quasi-dynamic approximation rather than explicitly incorporating inertial terms (Rice 1993).

We assume that friction on the fault follows the RSF law (Dieterich 1979; Ruina 1983). The shear stress $\tau_i(t)$ on cell i is related to the friction coefficient $\mu_i(t)$ and the effective normal stress σ_i as

$$\tau_i(t) = \mu_i(t)\sigma_i, \quad (2)$$

where $\mu_i(t)$ is given by

$$\mu_i(t) = \mu_0 + a_i \ln \frac{V_i(t)}{V_0} + b_i \ln \frac{V_0 \theta_i(t)}{d_{ci}}. \quad (3)$$

We assume that the state variable $\theta_i(t)$ evolves following the aging law (Ruina 1983);

$$\frac{d\theta_i(t)}{dt} = 1 - \frac{V_i(t)\theta_i(t)}{d_{ci}}. \quad (4)$$

Here, μ_0 is the reference friction coefficient at reference slip velocity V_0 . a_i , b_i , and d_{ci} are the frictional parameters. Frictional parameters and effective normal stress are constant in time. By combining and differentiating Equations (1)–(3), we obtain

$$\frac{dV_i(t)}{dt} = \left(\frac{a_i\sigma_i}{V_i(t)} + \frac{G}{2c} \right)^{-1} \left\{ \sum_{j=1}^{N_c} K_{ij}(V_j(t) - V_{pl}) - \frac{b_i\sigma_i}{\theta_i(t)} \left(1 - \frac{V_i(t)\theta_i(t)}{d_{ci}} \right) \right\}. \quad (5)$$

Equations (4) and (5) are numerically integrated using DOP853, a step-size-controlled Runge-Kutta method (Hairer et al. 1993), to simulate temporal evolution. Unless otherwise specified, the simulations start from steady-state conditions with an initial slip velocity $V_{init} = 0.9V_{pl}$ for the entire fault.

2.2 Frictional parameters and effective normal stress

The frictional parameters and the effective normal stress control the friction on the fault.

When $a_i - b_i > 0$, the friction is velocity-strengthening (VS) and produces stable sliding.

On the other hand, when $a_i - b_i < 0$, the friction is velocity-weakening (VW), and the slip can be unstable.

143 On a homogeneous VW fault, SSEs occur when the size of the slip region is large
 144 enough to accelerate to nucleate, but small enough not to reach seismic slip. Specifically,
 145 for a fault elongated along strike with the width W , SSEs are typically expected when W
 146 lies between two bounds: a few times h_{RR}^* yet still smaller than h_{3D}^* (Dal Zilio et al. 2020).
 147 Here, the critical nucleation size h_{RR}^* arises from a linear quasi-static stability analysis
 148 and marks the minimum unstable wavelength of perturbations (Rice and Ruina 1983).
 149 h_{3D}^* comes from an energy-balance argument for an expanding crack and provides an
 150 upper bound on the nucleation dimension associated with the transition from quasi-static
 151 to seismic slip (Rubin and Ampuero 2005; Chen and Lapusta 2009).

$$152 \quad h_{RR}^* = \frac{\pi}{4} \frac{G' d_c}{\sigma(b-a)}, \quad (6)$$

$$153 \quad h_{3D}^* = \frac{\pi}{2} \frac{G' b d_c}{\sigma(b-a)^2}, \quad (7)$$

154 where G' is the effective shear modulus, defined as $G' = G/(1 - \nu)$ for in-plane slip. We
 155 adopt this framework for SSEs following previous studies, including Dal Zilio et al.
 156 (2020) and Ohata (2023).

157 In this study, we set a VW region with $L_{VW} = 320$ km (X-axis) and $W_{VW} = 20$ km
 158 (Y-axis), located at the center of the fault, surrounded by a VS region. Throughout the

experiments, we fix the frictional parameters $a_{VW} = 0.01$ and $b_{VW} = 0.013$ in the VW region, while $a_{VS} = 0.01$ and $b_{VS} = 0.007$ in the surrounding VS region. The effective normal stress in the VW region, σ_{VW} , is also fixed at 5 MPa.

While fixing the parameters described above, we systematically vary the characteristic slip distance, d_c , assumed to be uniform across both the VW and VS regions. We vary d_c in the range of 4 to 6 mm, corresponding to $1.59 < W_{VW}/h^*_{RR} < 2.39$ and $0.18 < W_{VW}/h^*_{3D} < 0.28$, within the parameter range where SSEs are expected to occur. We also vary the effective normal stress in the VS region, σ_{VS} , from 2 to 100 MPa, to investigate the conditions controlling SSE behavior.

3 Results

The slip in the VW region is categorized into four types: three types of SSEs and steady slip, where the entire fault slides stably at the long-term slip velocity V_{pl} . In all SSE scenarios, slip segments spontaneously, even with homogeneous model settings, as reported in previous studies (Dal Zilio et al. 2020; Ohata 2023). It takes time for the segmentation to develop and the slip patterns to stabilize. Subsection 3.1 demonstrates

the process leading to SSE segmentation. Next, we present the slip patterns of the three types of SSEs, each illustrated with representative examples (Subsection 3.2), and the dependence of slip types on σ_{VS} and d_c (Subsection 3.3). Finally, we discuss the diversity in the number and size of segments observed in our simulations depending on the initial condition in Subsection 3.4.

3.1 *Spontaneous SSE segmentation*

Here, we demonstrate how SSEs on a homogeneous fault spontaneously evolve into segmented slip patterns. Figure 2 shows the evolution of slip velocity along the X-axis for the case with $\sigma_{VS} = 5$ MPa and $d_c = 4.375$ mm, focusing on the first 50 years until the slip pattern stabilizes. Since the model settings, including the initial conditions, are symmetric with respect to the X- and Y-axes, the resulting slip evolution maintains the symmetry.

The slip initially propagates uniformly along strike from the fault edges toward its center (Time ~ 0 —2 years). As SSEs recur, however, spatial heterogeneity in slip velocity gradually emerges. For example, around Time ~ 10 years, the slip localizes in

the central region and then bilaterally propagates toward the edges. The direction of slip propagation repeatedly reverses, alternating between center-to-edges and edges-to-center, and the spatial heterogeneity of slip velocity becomes more intense. Eventually, the slip converges to a stable pattern with seven relatively high-velocity regions, which can be regarded as the SSE segments. Although the final slip pattern varies depending on the model settings, such as σ_{VS} and d_c , the gradual development of the spatial heterogeneity follows a similar process in all SSE cases.

We attribute the spontaneous segmentation to the heterogeneity induced by the edges. The boundaries between the VW and VS regions arrest slip propagation, generating local heterogeneity in stress and slip velocity near the boundaries. This heterogeneity progressively evolves with recurring SSEs, causing the spontaneous segmentation of SSEs along strike.

3.2 Slip patterns of SSEs

The slip patterns of SSEs depend on σ_{VS} and d_c and are classified into three types: “periodic”, “quasi-periodic”, and “chaotic”. Figure 3 shows representative examples of

207 these three types: (a) the periodic type ($\sigma_{VS} = 5$ MPa), (b) the quasi-periodic type ($\sigma_{VS} =$
208 30 MPa), and (c) the chaotic type ($\sigma_{VS} = 100$ MPa), all with d_c fixed at 4.375 mm. To
209 focus on the stabilized slip behavior, we plot the slip velocity over a 10-year interval
210 starting from Time = 190 years.

211 The periodic type (Figure 3a) is characterized by perfectly periodic slip evolution.
212 The segments are spatially fixed, and all segmented SSEs recur at the same interval. Then,
213 the recurrent interval of the entire fault slip matches that of each segmented SSE. The
214 segment sizes are nearly uniform along strike, though those near the edges are slightly
215 smaller. The spatiotemporally regular SSEs on persistent segments reported by Ohata
216 (2023) correspond to this periodic type.

217 The quasi-periodic type (Figure 3b) is similar to the periodic type; the location of
218 the segments is nearly fixed, and the recurrence interval is almost constant, but with slight
219 modulation across cycles. The boundaries of the segments migrate slightly, and the cycle
220 never becomes perfectly periodic. In some cases, such as in Figure 3(b), the spatial
221 contrast in slip velocity is relatively small, making the segmentation less distinct than in
222 the periodic type.

223 The chaotic type (Figure 3c) is far from regular. Both segment sizes and the
224 boundaries frequently vary spatiotemporally, indicating complex, possibly chaotic slip
225 behavior, compared to the other two types. This chaotic type corresponds to the SSEs
226 with various sizes reported by Dal Zilio et al. (2020).

227 As shown above, we have successfully reproduced the diversity of SSE patterns
228 on a homogeneous fault reported in previous studies. The examples in Figure 3 differ
229 only in σ_{VS} , while the settings in the VW region are the same, indicating that the slip
230 pattern of SSE is strongly dependent on the conditions of the surrounding region.

231

232 3.3 *Dependence of slip types on σ_{VS} and d_c*

233 Figure 4 illustrates the dependence of slip patterns in the VW region on σ_{VS} and d_c . The
234 boundary between the unstable-slip (SSE) and steady-slip regimes forms a curve that is
235 convex to the left, with its peak at $\sigma_{VS} \sim 10$ MPa. As d_c increases, the slip consistently
236 transitions from SSEs to stable slip for all σ_{VS} values. This trend is attributed to the
237 increase in the critical nucleation size h^* with d_c , which makes the spontaneous
238 development of unstable slip more difficult.

239 On the other hand, the slip stability exhibits non-monotonic dependence on σ_{VS} .
240 For example, at $d_c = 4.5$ mm, the slip in the VW region transitions from unstable to stable,
241 and then back to unstable as σ_{VS} increases. This non-monotonic dependence is discussed
242 further in Subsection 4.2.

243 Within the unstable regime exhibiting SSEs, the periodic type appears in the
244 relatively low σ_{VS} region, while the chaotic type dominates the high σ_{VS} region. The quasi-
245 periodic type is generally located in the intermediate region, suggesting a transitional state
246 between the two types. The underlying physics of the variation in SSE patterns is
247 discussed in Subsection 4.3.

248

249 3.4 Segment size and number of the periodic SSEs

250 In the chaotic type, SSEs with various sizes occur in a single simulation run, as shown in
251 Figure 3(c). The size distribution of such SSEs has been well investigated in Dal Zilio et
252 al. (2020). On the other hand, in the periodic type, the segment size is nearly uniform in
253 space and time within a single simulation.

254 In the case shown in Figure 3(a), seven segments appear in the VW region, which

255 spans $L_{VW} = 320$ km along strike. Then, the size of each segment is roughly 45 km.
 256 However, we found that the number of segments can vary with different initial conditions,
 257 even for the same frictional properties. In this subsection, we investigate the variation in
 258 the size and number of the segmented periodic SSEs by applying initial conditions with
 259 specific spatial scales, instead of the uniform condition.

260 We set the initial condition for the slip velocity in the VW region, $V_{init}(X)$, with
 261 k peaks along strike,

$$262 \quad V_{init}(X) = \begin{cases} V_{pl} + 0.9V_{pl} \sin\left(\frac{2\pi(k/2)}{L_{VW}}X\right) & (k: \text{even}) \\ V_{pl} + 0.9V_{pl} \cos\left(\frac{2\pi(k/2)}{L_{VW}}X\right) & (k: \text{odd}) \end{cases}, \quad (8)$$

263 while the initial velocity distribution is uniform along the Y-axis. The initial slip velocity
 264 in the VS region is uniform and set to V_{pl} . The initial value of θ is set to its steady-state
 265 value over the entire fault, i.e., $\theta_{init} = d_c/V_{init}$.

266 Figure 5 shows the results for $k = 4, 5, 9$, and 10. The values of σ_{VS} and d_c are fixed
 267 at 5 MPa and 4.375 mm, respectively, identical to those in Figure 3(a). In Figures 5(b)
 268 and 5(c), the number of initial velocity peaks k matches the number of resulting SSE
 269 segments, five and nine, respectively. On the other hand, in Figures 5(a) and 5(d), the

initial velocity peaks, $k = 4$ and 10, evolve into different numbers of SSE segments: six and eight, respectively.

These results indicate that the number of segments cannot take arbitrary values but appears to have upper and lower limits. For the parameter set shown above, regardless of the initial wavenumber, the final number of segments consistently settles between five and nine, corresponding to a rough segment length of 35—62 km, varying by about a factor of two. This implies that the SSE segment size is not solely determined by the nucleation size h^* , although the along-strike segment size falls within the theoretical range for producing SSEs: a few times larger than $h_{RR}^* \sim 9$ km and smaller than $h_{3D}^* \sim 79$ km. The preferred number of segments is discussed in Subsection 4.3.

4 Discussion

4.1 Slip in the VS Region

We have shown that the slip patterns in the VW region depend strongly on the surrounding VS region. In this subsection, we focus on slip variation in the VS region and examine its effect on the VW region.

Figure 6 illustrates the evolution of shear stress and slip velocity for the cases $\sigma_{VS} = 5$ MPa and 100 MPa, corresponding to the cases shown in Figures 3(a) and 3(b), respectively. For each case, the shear stress along the Y-axis is shown in Figures 6(a) and 6(b), as relative to the reference value, $\tau - \tau^*$, where $\tau^* = \sigma[a \ln(V^*/V_0) + b \ln(V_0\theta^*/d_c)]$, for 100 days after the shear stress at origin (point O) reaches its peak value during an SSE cycle. V^* and θ^* are defined as

$$V^* = V_{pl}, \quad \theta^* = \frac{d_c}{V_{pl}}. \quad (9)$$

The slip velocities at points O and A, located at the center and just outside the VW region, respectively, are also plotted in Figures 6(c) and 6(d).

In both cases, as the VW region slips during an SSE, the shear stress in the VW region decreases and is transferred to the surrounding VS region. The VS region instantaneously responds to the transferred stress by increasing slip velocity. However, the subsequent spatiotemporal slip evolution differs significantly depending on σ_{VS} . When σ_{VS} is low, the slip velocity increases rapidly across a wide area along the Y-axis within the VS region. Then, the VS region slips synchronously with the VW region as part of the SSE, releasing the accumulated stress quickly. On the other hand, when σ_{VS} is

high, the VS region accelerates slowly, and the slip is confined to the area adjacent to the VW region. It takes several tens of days for the VS region to slip, and the slip is interpreted as afterslip following the SSE in the VW region.

The observed difference in slip behavior in the VS region indicates a difference in the effective SSE size along the Y-axis. Higher σ_{VS} corresponds to a decrease in effective SSE size, suggesting an increase in the apparent stiffness of the SSE region. Based on these observations, one would intuitively expect a monotonic increase in slip stability in the VW region as σ_{VS} increases.

4.2 Non-monotonic dependence of slip stability on σ_{VS}

The observation in Subsection 4.1 intuitively suggests a monotonic increase in slip stability within the VW region for higher σ_{VS} , attributed to the decrease in SSE size along the Y-axis. However, the simulation results in Section 3.3 demonstrate a non-monotonic dependence. To understand this non-monotonic behavior, we employ a two-degree-of-freedom spring-block (2DOF) model (e.g., Yoshida and Kato 2003) with the RSF law as an analogue of our continuum model and perform a linear stability analysis.

318

319 *4.2.1 2DOF spring-block model*

320 We employ a 2DOF spring-block model (Figure 7) consisting of Blocks 1 and 2, which
321 represent the VW region and the surrounding VS region of the continuum model,
322 respectively. Each block is connected to a driver moving at a constant velocity V_{pl} via a
323 spring of stiffness k_d , and the blocks are coupled by a spring of stiffness k_c . The stiffness
324 is normalized by the base area of the block, identical for both blocks. The quasi-dynamic
325 equations of motion for the two blocks gives the shear stress of each block τ_i as

326
$$\tau_1(t) = k_d (V_{pl}t - x_1(t)) + k_c (x_2(t) - x_1(t)) - \frac{G}{2c} V_1(t), \quad (10)$$

327
$$\tau_2(t) = k_d (V_{pl}t - x_2(t)) - k_c (x_2(t) - x_1(t)) - \frac{G}{2c} V_2(t). \quad (11)$$

328 The substitute i denotes the block number. The frictional coefficient of each block obeys
329 the RSF law with the aging law:

330
$$\mu_i(t) = \frac{\tau_i(t)}{\sigma_i} = \mu_0 + a_i \ln \frac{V_i(t)}{V_0} + b_i \ln \frac{V_0 \theta_i(t)}{d_{ci}}, \quad (12)$$

331
$$\frac{d\theta_i(t)}{dt} = 1 - \frac{V_i(t)\theta_i(t)}{d_{ci}}. \quad (13)$$

332 In our analysis, we set the frictional and loading parameters as follows: $a_1 = a_2 =$
333 0.01 , $b_1 = 0.013$, $b_2 = 0.007$, $\sigma_1 = 5$ MPa, $V_{pl} = 10^{-9}$ m/s, and $k_d = k_c = 2 \times 10^6$ Pa/m. We

334 selected the stiffness values to ensure that the frictional parameters and the effective
335 normal stress are of the same order of magnitude as those in the continuum model. With
336 these parameters fixed, we set $d_{c1} = d_{c2} = d_c$ and numerically solve the slip evolution by
337 varying σ_2 and d_c .

338 Figure 8 shows the maximum slip velocity of Block 1 (the VW block) for each
339 simulation. At small d_c , Block 1 exhibits recurring unstable slip events, whereas at large
340 d_c it produces steady sliding at V_{pl} . The boundary between the unstable and stable regimes
341 is distinct and convex to the left with its peak at $\sigma_2 \sim 10$ MPa. This boundary shape is
342 consistent with that of the continuum model shown in Figure 4, showing a non-monotonic
343 dependence of slip stability on σ_2 .

344 Figure 9 illustrates the evolution of slip velocities of Blocks 1 and 2 for the cases
345 $\sigma_2 = 1$ and 50 MPa, with d_c fixed at 3 mm. Under low σ_2 (Figure 9a), Block 2 (the VS
346 block) slips almost simultaneously with Block 1. In contrast, under high σ_2 (Figure 9b),
347 Block 2 gradually accelerates following the unstable slip of Block 1. The slip of Block 2
348 extends over several tens of days. In the former case, Block 2 behaves as part of the SSE
349 together with Block 1, whereas in the latter it behaves as afterslip following the slip event

on Block 1. These behaviors of Block 2 are comparable to those of the VS region in the continuum model (Figures 6c and 6d).

Based on these observations, we conclude that the 2DOF model successfully captures the non-monotonic dependence on σ_{VS} of the slip stability and the model feature observed in the continuum model and can be regarded as a plausible analogue.

4.2.2 Linear stability analysis

To analytically investigate slip stability, we perform a linear stability analysis of the 2DOF model, which is analytically more tractable than the original continuum model.

Luo and Ampuero (2018) investigated a heterogeneous fault model consisting of alternating VW and VS regions. They simplified the system into a 2DOF model, in which a pair of VW and VS blocks with an arbitrary VW/VS area ratio ($1:f$) forms a fundamental repeating unit under periodic boundary conditions, and performed a linear stability analysis. The governing equation of our 2DOF model corresponds to theirs for $f=1$.

Following their procedure, we linearize the governing equations around a

reference steady state, defined by $V_1 = V_2 = V^*$ and $\theta_1 = \theta_2 = \theta^*$ (V^* and θ^* : Equation 9), and formulate an eigenvalue problem. The stability boundary is then obtained from the condition that the real part of the leading eigenvalue crosses zero. We omit the radiation damping term, following Luo and Ampuero (2018). Unlike Luo and Ampuero (2018), who assumed the slip law (Ruina 1983) for the state variable evolution, this study employs the aging law. The condition at the stability boundary is given by

$$s_1(s_4s_1 - s_2s_3) + s_0s_3^2 = 0, \quad (14)$$

where s_0 — s_4 are defined in our case as

$$\begin{cases} s_0 = k_d(k_d + 2k_c) \\ s_1V_{pl} = 2k_d(k_d + 2k_c)d_c + (A_1 - B_1 + A_2 - B_2)(k_d + k_c) \\ s_2V_{pl}^2 = k_d(k_d + 2k_c)d_c^2 + (A_1 - B_1)(A_2 - B_2) + d_c(k_d + k_c)(2A_1 + 2A_2 - B_1 - B_2). \\ s_3V_{pl}^3 = 2A_1A_2d_c - (A_1B_2 + A_2B_1)d_c + (A_1 + A_2)(k_d + k_c)d_c^2 \\ s_4V_{pl}^4 = A_1A_2d_c^2 \end{cases} \quad (15)$$

Here, $A_i = a_i\sigma_i$ and $B_i = b_i\sigma_i$ for $i = 1, 2$. The analytical condition for the stability boundary (Equation 14) takes the same form as Equation (18) in Luo and Ampuero (2018). See the details of the derivation in their paper.

Equation (14) cannot be analytically inverted to express d_c as an explicit function of σ_2 . Therefore, we solve it numerically. The derived stability boundary is plotted as a red line in Figure 8. It agrees well with the boundary between the stable and unstable

381 regimes obtained from the 2DOF model simulations. The non-monotonic dependence of
 382 slip stability on σ_{VS} in the original continuum model (Figure 4) is likely governed by the
 383 same mechanism as in the 2DOF model.

384 In the limits of high and low σ_2 , the stability boundary approaches vertical lines.
 385 Although the equations defining the stability boundary are too complicated to understand
 386 intuitively, a physical explanation is possible for these σ_2 limits using the concept of
 387 critical stiffness of the one-degree-of-freedom spring–block model,

$$388 \quad k_{crit} = \frac{\sigma(b-a)}{d_c}, \quad (16)$$

389 derived by Ruina (1983). When $\sigma_2 \rightarrow \infty$, Block 2 moves rigidly with the driver at a
 390 constant velocity V_{pl} , unperturbed by the slip of Block 1. In this limit, the system becomes
 391 equivalent to a model in which Block 1 is connected to the driver via two parallel springs
 392 with stiffnesses k_d and k_c , yielding an apparent stiffness $k_d + k_c$. The condition for the
 393 stability boundary is then,

$$394 \quad k_d + k_c = \frac{\sigma_1(b_1 - a_1)}{d_c}. \quad (17)$$

395 When $\sigma_2 \rightarrow 0$, the frictional resistance of the Block 2 vanishes, and it behaves merely as
 396 a mechanical connector. Then, the system is equivalent to a model in which Block 1 is

397 connected to the driver by a single spring of stiffness k_d in parallel with another branch
 398 consisting of two springs of stiffness k_d and k_c connected in series. The corresponding
 399 condition for the stability boundary is then given by

$$400 \quad k_d + (k_d^{-1} + k_c^{-1})^{-1} = \frac{\sigma_1(b_1 - a_1)}{d_c}. \quad (18)$$

401 In Figure 8, we confirm that the asymptotic formulae given by Equations (17) and (18)
 402 (white dashed lines) explain the linear stability boundary (red line) well.

403

404 4.3 *Spatial patterns of SSEs: Linear stability analysis of the continuum model*

405 In the unstable regime, higher σ_{VS} tends to produce chaotic SSEs, while lower σ_{VS}
 406 produces periodic SSEs. To investigate the diversity of slip patterns in the unstable regime,
 407 we apply the linear stability analysis to the original continuum model in this section.

408 As in the 2DOF case, we linearize the continuum model around the steady state.

409 In this analysis, we derive eigenvalues corresponding to the perturbation's growth rates
 410 and eigenvectors representing the spatial modes of the slip pattern. We consider the
 411 deviation of variables from the steady-state;

$$412 \quad V_i = V_i^* + \delta V_i, \quad \theta_i = \theta_i^* + \delta \theta_i, \quad (19)$$

413 where steady state is set at $V_i^* = V^*$ and $\theta_i^* = \theta^*$ (V^* and θ^* : Equation 9) for the entire fault.

414 Starting from Equation (1) with the radiation damping term neglected, differentiation and

415 perturbation expansion yield

$$416 \quad \delta \dot{\tau}_i = \sum_{j=1}^{N_c} K_{ij} \delta V_j. \quad (20)$$

417 From Equation (2), taking derivatives and neglecting the second-order term, perturbations

418 give

$$419 \quad \delta \dot{\tau}_i \approx \sigma_i \left(\frac{a_i}{V_i^*} \delta \dot{V}_i + \frac{b_i}{\theta_i^*} \delta \dot{\theta}_i \right). \quad (21)$$

420 Linearization of Equation (4) results in

$$421 \quad \delta \dot{\theta}_i \approx -\frac{1}{V_i^*} \delta V_i - \frac{1}{\theta_i^*} \delta \theta_i. \quad (22)$$

422 Combining Equations (20) and (21) and substituting Equation (22), we obtain

$$423 \quad \delta \dot{V}_i = \frac{V_i^*}{a_i \sigma_i} \left(\sum_{j=1}^{N_c} K_{ij} \delta V_j + \frac{b_i \sigma_i}{d_{ci}} \delta V_i \right) + \frac{b_i \sigma_i}{\theta_i^{*2}} \delta \theta_i. \quad (23)$$

424 Then, Equations (22) and (23) give the derivatives of the deviations. These are expressed

425 in matrix form as:

$$426 \quad \begin{cases} \frac{d}{dt} \begin{pmatrix} \delta \mathbf{V} \\ \delta \boldsymbol{\theta} \end{pmatrix} = \mathbf{J} \begin{pmatrix} \delta \mathbf{V} \\ \delta \boldsymbol{\theta} \end{pmatrix} \\ \mathbf{J} = \begin{bmatrix} D_a(K + K_b) & D_a M \\ A & B \end{bmatrix} \end{cases} \quad (24)$$

427 where $K = (K_{ij})$ denotes the slip response function matrix. $D_a = \text{diag} \left(\frac{V_i^*}{a_i \sigma_i} \right)$, $K_b =$

428 $\text{diag}\left(\frac{b_i\sigma_i}{d_{ci}}\right)$, $M = \text{diag}\left(\frac{b_i\sigma_i}{\theta_i^{*2}}\right)$, $A = \text{diag}\left(-\frac{1}{V_i^*}\right)$, and $B = \text{diag}\left(-\frac{1}{\theta_i^*}\right)$.

429 The eigenvalue problem governs the stability of the steady state,

430
$$J\mathbf{y} = \lambda\mathbf{y}, \quad \mathbf{y} = \begin{pmatrix} \delta V \\ \delta \theta \end{pmatrix}. \quad (25)$$

431 If the real part of the eigenvalue, $\text{Re}(\lambda)$, is positive, the perturbation with the spatial mode
 432 corresponding to the associated eigenvector can develop. We numerically solved the
 433 eigenvalue problem for a $2 \text{ km} \times 2 \text{ km}$ mesh, yielding $N_c = 9,000$. Because J contains a
 434 large fraction of zeros, we stored it in a sparse format and computed the eigenpairs using
 435 SciPy's sparse linear-algebra routines (`scipy.sparse` and `scipy.sparse.linalg.eigs`).

436 Figure 10 presents the results of the low σ_{VS} case, which produces periodic-type
 437 SSEs, corresponding to point (a) in Figure 4 ($\sigma_{VS} = 5 \text{ MPa}$ and $d_c = 4.375 \text{ mm}$). The spatial
 438 structures of the eigenvectors δV (Figure 10a) exhibit clear along-strike segmentation
 439 within the VW region. The value of $\text{Re}(\lambda)$ is plotted in Figure 10(b) with respect to the
 440 number of along-strike segments observed in the corresponding δV . The distribution of
 441 $\text{Re}(\lambda)$ is convex upward with a maximum value at seven segments.

442 Numerical simulations typically produce 5—9 segments (Section 3.4), and the
 443 case initialized with a uniform condition shows seven segments (Figure 3a). These

444 correspond to the spatial modes of the eigenvectors associated with large $\text{Re}(\lambda)$ values.
445 While the linear analysis predicts the unstable modes ($\text{Re}(\lambda) > 0$) for 2—14 segments
446 (Figure 10b), not all these numbers actually emerge in nonlinear simulations. This
447 indicates the importance of the growth rate magnitude: spatial modes with larger $\text{Re}(\lambda)$
448 dominate, resulting in a limited range of realized segments.

449 For high σ_{VS} , the linear stability analysis yields the results shown in Figure 11.
450 The parameters are set to $\sigma_{VS} = 100$ MPa and $d_c = 4.375$ mm, corresponding to point (c)
451 in Figure 4, where chaotic SSEs occur. In contrast to the periodic SSE case, the highest
452 $\text{Re}(\lambda)$ corresponds to uniform slip of the entire fault (single-segment mode), followed in
453 order by modes with progressively increasing segment numbers. In numerical simulations,
454 however, this predicted single-segment SSE is not observed. Instead, the actual slip
455 evolution exhibits no coherent along-strike segmentation and is chaotic in time and space.

456 A plausible explanation is that modes with very few segments are physically
457 unsustainable because their wavelengths are far greater than the nucleation size h^* . While
458 such lower-order modes may initially develop, they cannot be sustained. Consequently,
459 the slip does not settle into a stable segmentation pattern. Instead, the superposition of

these transient modes results in a chaotic slip pattern that masks the spatial structure of each mode.

In summary, the linear stability analysis successfully demonstrates the fundamental difference between the low and high σ_{VS} regimes. While the linear theory well explains the low σ_{VS} case, the behavior in the high σ_{VS} regime reveals that the realized slip patterns are governed not only by the linear growth rate but also by the sustainability of the modes relative to the nucleation size.

5 Conclusion

In this study, we investigated the dynamics of the slow slip events (SSEs) on a homogeneous planar fault with velocity-weakening (VW) properties, elongated along strike. The slip behavior on such a homogeneous fault is categorized into two regimes: stable and unstable regimes producing steady sliding and SSEs with spontaneous segmentation, respectively. Within the unstable regime, slip patterns are further classified into three distinct types: periodic, quasi-periodic, and chaotic. Periodic SSEs are characterized by spatiotemporally regular segmentation, while chaotic SSEs exhibit

frequently varying segment sizes and boundaries. The quasi-periodic SSEs are regarded as a transition between the two.

While this diversity of SSE patterns has been reported in the previous studies, we found that it is strongly controlled by the condition of the surrounding velocity-strengthening (VS) region. Even with identical frictional properties in the VW region, increasing the effective normal stress of the VS region, σ_{VS} , alters the slip stability of the VW region in a non-monotonic manner. Furthermore, within the unstable regime, the slip pattern typically changes from periodic to chaotic as σ_{VS} increases.

This transition arises from differences in slip behavior within the VS region. Under lower σ_{VS} , the rupture area of the SSE expands into the VS region, resulting in the VS region slipping as part of the SSE. On the other hand, under higher σ_{VS} , the SSE is confined within the VW region, and the VS region slips as an afterslip of the SSE. Then, the effective SSE size decreases as σ_{VS} increases.

A simplified two-degree-of-freedom (2DOF) spring-slider model, consisting of VW and VS blocks, successfully captures the non-monotonic change in slip stability observed in the continuum model. This simplified model analogously provides us with

492 an understanding of the non-monotonic stability transition through linear stability
493 analysis.

494 Linear stability analysis of the original continuum model also reveals the
495 fundamental difference between periodic and chaotic SSE patterns. In the low σ_{VS} case
496 (periodic SSE regime), the realized spatial patterns of SSE segments correspond to the
497 spatial mode of the linearized perturbation with the large growth rate. On the other hand,
498 in the high σ_{VS} case (chaotic SSE regime), the predicted single-segment mode is
499 physically unsustainable because its size is much larger than the nucleation size. In this
500 regime, stable segmentation cannot be established; instead, the system exhibits chaotic
501 behavior.

502 These results provide a better understanding of the slip dynamics on homogeneous
503 faults observed in previous numerical studies. We conclude that the conditions in the
504 surrounding region of the SSE fault are fundamental control factors on whether SSEs
505 exhibit regular recurrence or chaotic complexity. Although we specifically focused on the
506 effective normal stress of the surrounding stable region, other factors that control SSE

507 expansions, such as the location or the strength of the neighboring coupling region, should
508 have a similar effect.

509

510 **Declarations**

511 **Ethics approval and consent to participate**

512 Not applicable.

513 **Consent for publication**

514 Not applicable.

515 **List of abbreviations**

516 SSE slow slip event

517 RSF rate- and state-friction

518 VW velocity-weakening

519 VS velocity-strengthening

520 2DOF two-degree-of-freedom

521 **Availability of data and materials**

522 Not applicable. No datasets were used in the present study.

523 **Competing interests**

524 The authors declare no competing interests.

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530 **Authors' contributions**

531 K. N. performed the numerical experiments and drafted the manuscript. M.
532 O. and K. H. modified the manuscript. All authors discussed the results
533 and approved the final manuscript.

534

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542

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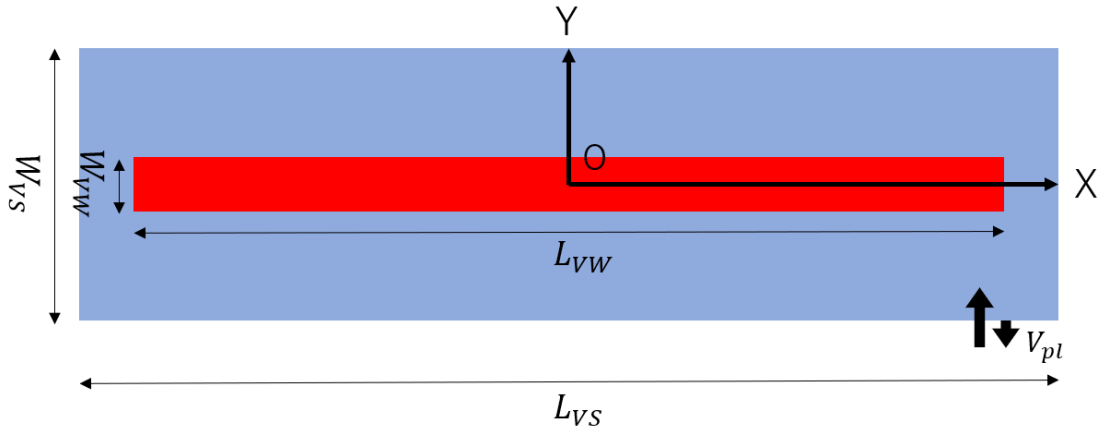
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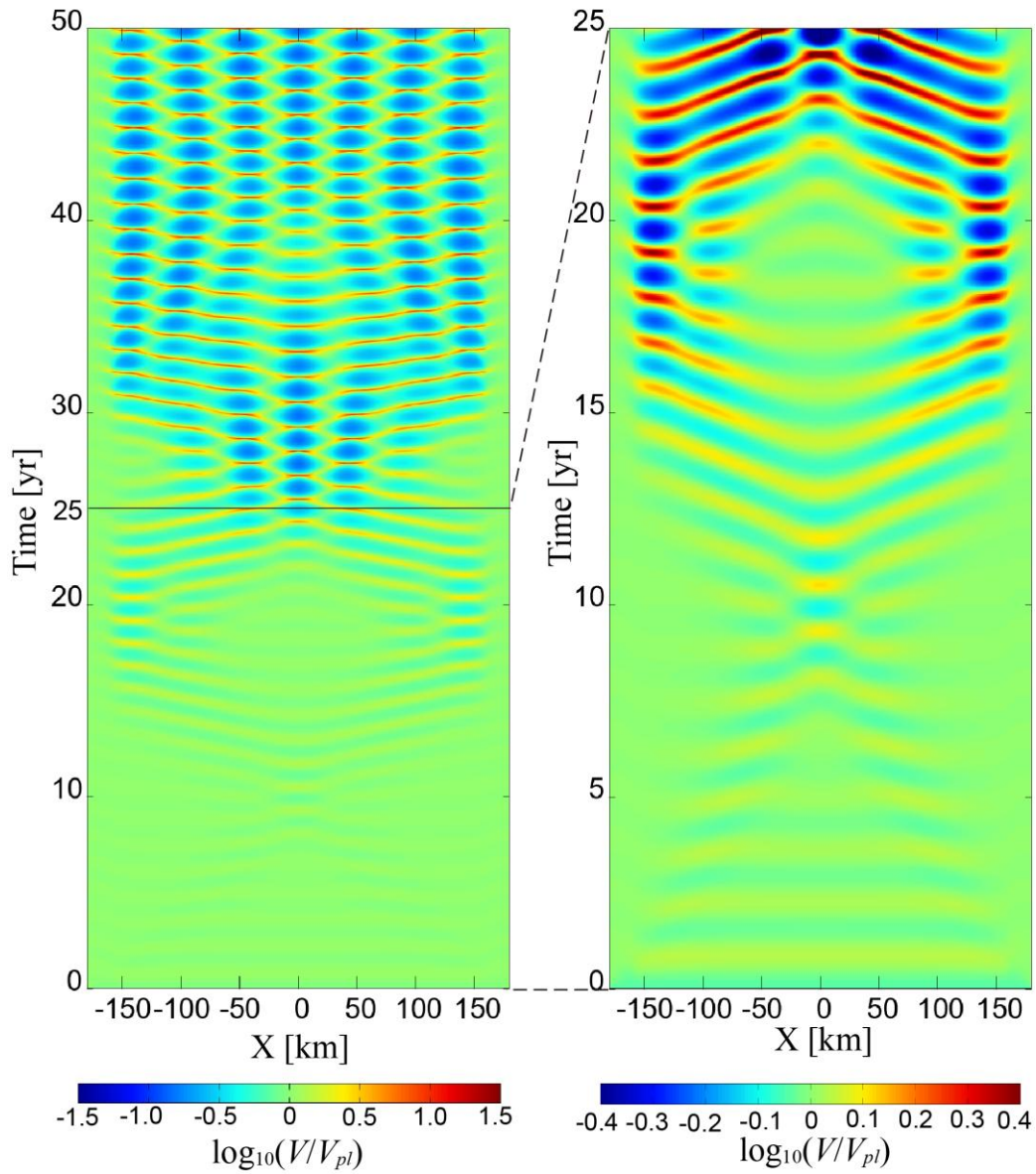
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649 **Figures**



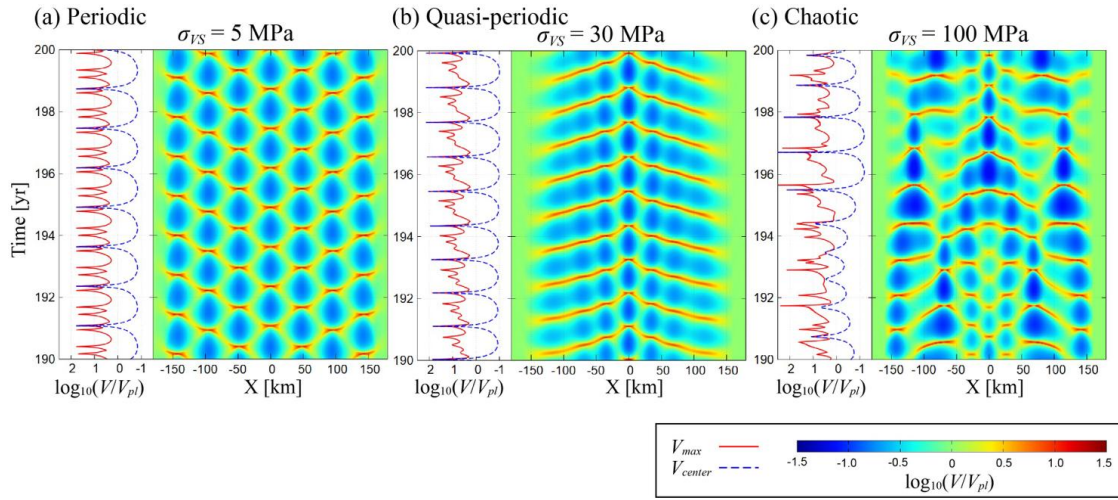
651 Figure 1; *Geometry of the fault model*; A planar fault spanning L_{VS} and W_{VS} along the X-
652 and Y-axes, embedded in a three-dimensional infinite homogeneous elastic medium. The
653 origin O is located at the center of the fault. The fault is loaded along the Y-axis, and the
654 long-term slip velocity is set to V_{pl} . The blue region represents a velocity-strengthening
655 (VS) region, while the red area represents a velocity-weakening (VW) region of
656 dimensions L_{VW} and W_{VW} . The exterior of the simulated fault is assumed to slip uniformly
657 at a velocity of V_{pl} .

658



659

660 Figure 2; *Initial evolution of slip velocity*; The evolution of slip velocity along the X-axis
 661 is shown as $\log_{10}(V/V_{pl})$ for the case with $\sigma_{VS} = 5$ MPa and $d_c = 4.375$ mm. The left and
 662 right panels display the evolution over the first 50 and 20 years, respectively. Note that
 663 the color scales of the two panels are different.



664

665 Figure 3; *Representative examples of SSE patterns*; The evolution of slip velocity for (a)

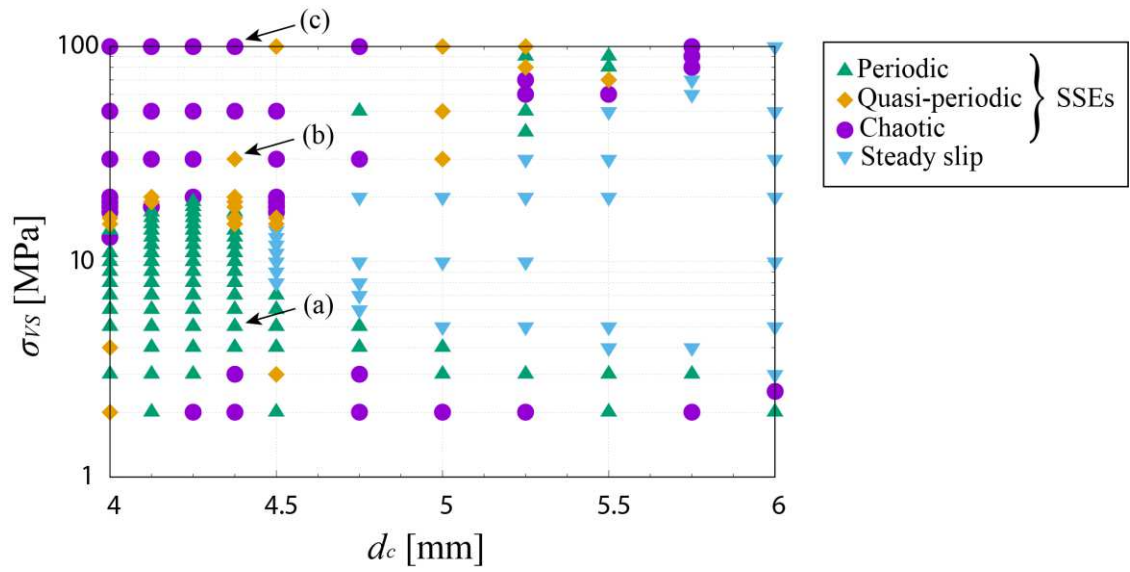
666 periodic ($\sigma_{VS} = 5$ MPa), (b) quasi-periodic ($\sigma_{VS} = 30$ MPa), and (c) chaotic ($\sigma_{VS} = 100$

667 MPa) SSEs. In all cases, d_c is fixed at 4.375 mm. The details of the color maps are the

668 same as in Figure 2(a), but for a time window of 190–200 years. The trajectories of the

669 maximum slip velocity over the fault and the slip velocity at point O in Figure 1 are also

670 plotted with a red solid line and a blue dashed line, respectively.



671

672

673 Figure 4; *Slip patterns for different σ_{VS} and d_c* ; Symbols represent different types of slip:

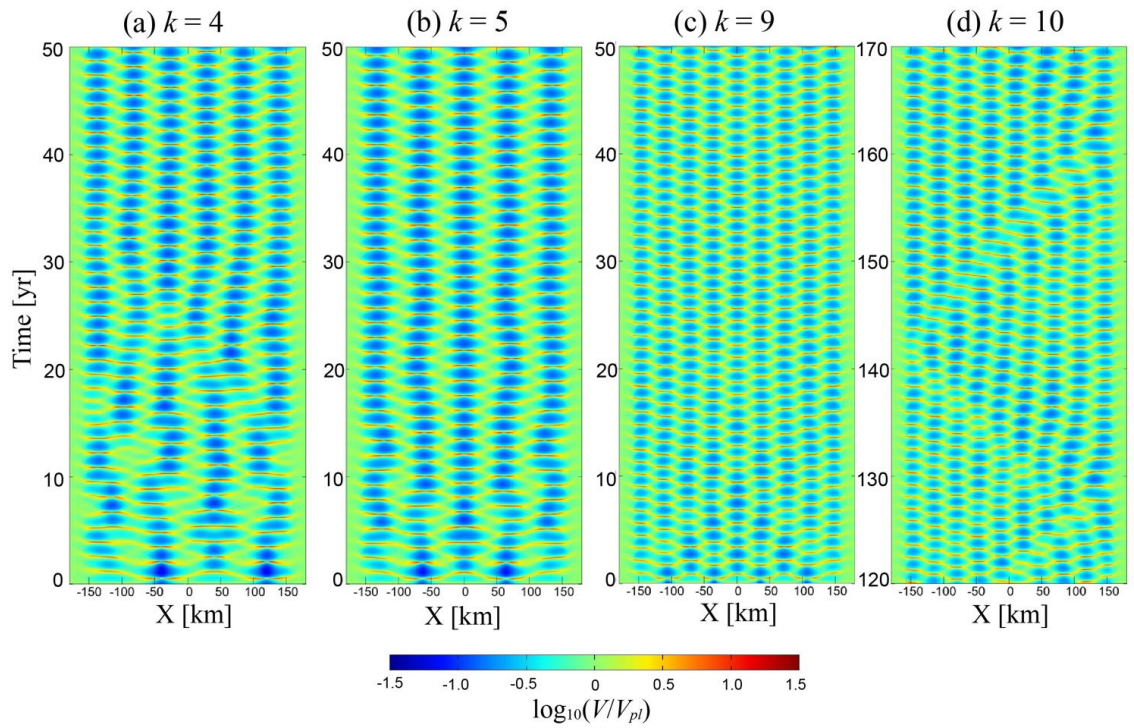
674 periodic (green triangles), quasi-periodic (orange diamonds), and chaotic (purple circles)

675 SSEs, and stable sliding (blue inverted triangles). The arrows labeled (a)—(c) indicate

676 the parameter sets corresponding to the representative examples shown in Figures 3(a)—

677 (c).

678



679

680 Figure 5; *Dependence of slip patterns on initial conditions*; Spatiotemporal evolution of

681 slip velocity for $\sigma_{VS} = 5$ MPa and $d_c = 4.375$ mm, starting from different initial conditions

682 with varying numbers of velocity peaks. The format is similar to Figure 2 but shows a

683 time window of 50 years. The initial number of peaks, k , is set to (a) 4, (b) 5, (c) 9, and

684 (d) 10. In all cases, the slip patterns converge to stable states exhibiting (a) 6, (b) 5, (c) 9,

685 and (d) 8 peaks along the X-axis, respectively.

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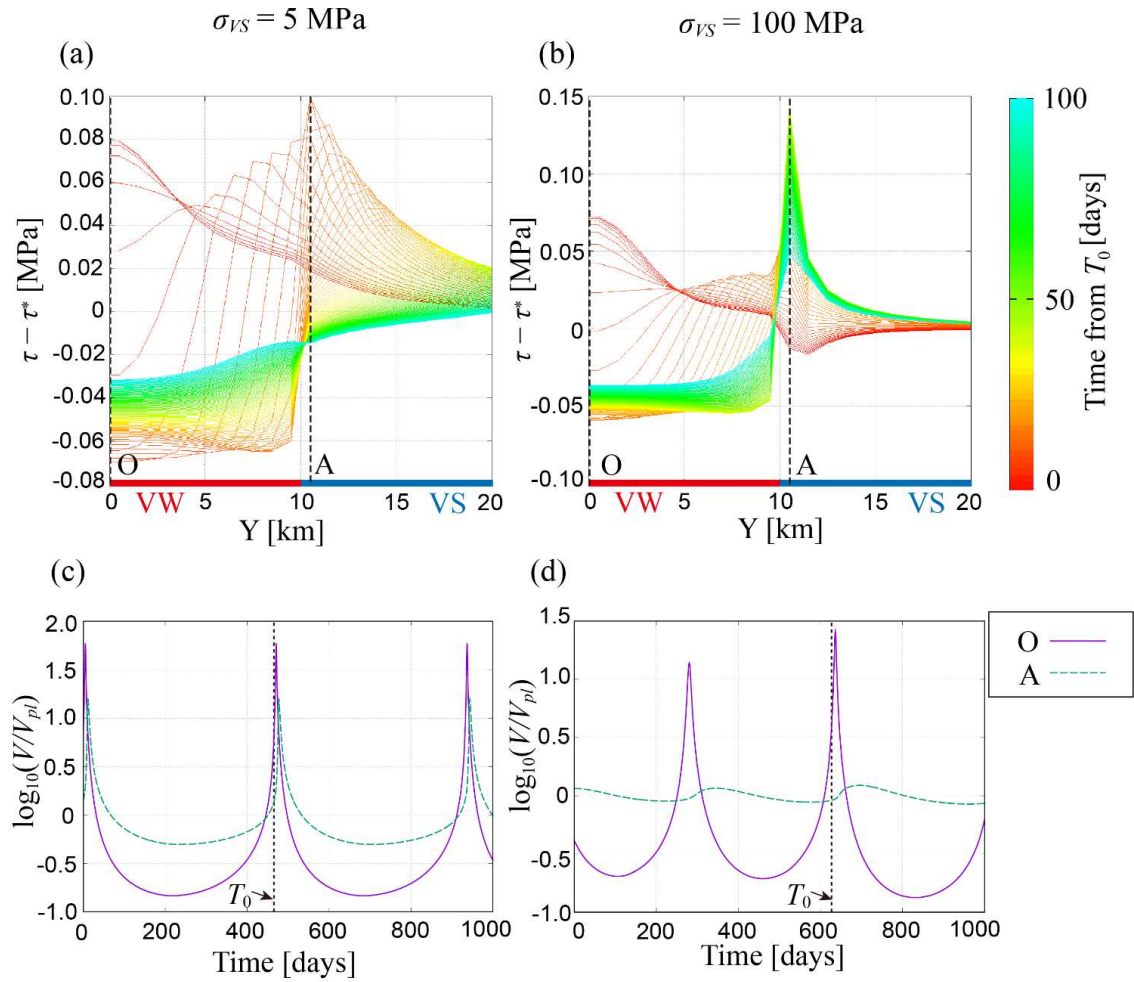
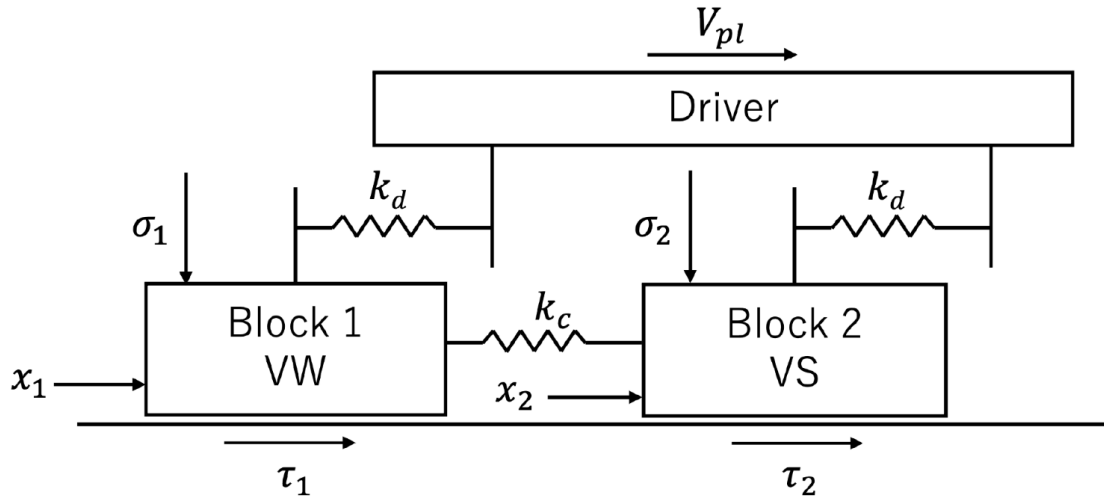


Figure 6; Evolution of shear stress and slip velocity during a single SSE; (a) and (b) Shear stress $\tau - \tau^*$ along the Y-axis for the cases $\sigma_{VS} = 5$ MPa and 100 MPa, respectively. The lines represent profiles at one-day intervals for 100 days starting from Time = T_0 , which is indicated in panels (c) and (d). The color indicates the time. (c) and (d) Time evolution of slip velocity at point O (center of the VW region) and point A (X = 0, Y = 10.5 km; just outside the VW region). The locations of the points O and A are indicated by the dashed lines in panels (a) and (b).



696

697 Figure 7; *Schematic view of the 2DOF spring-block model*; Blocks 1 and 2 with VW and

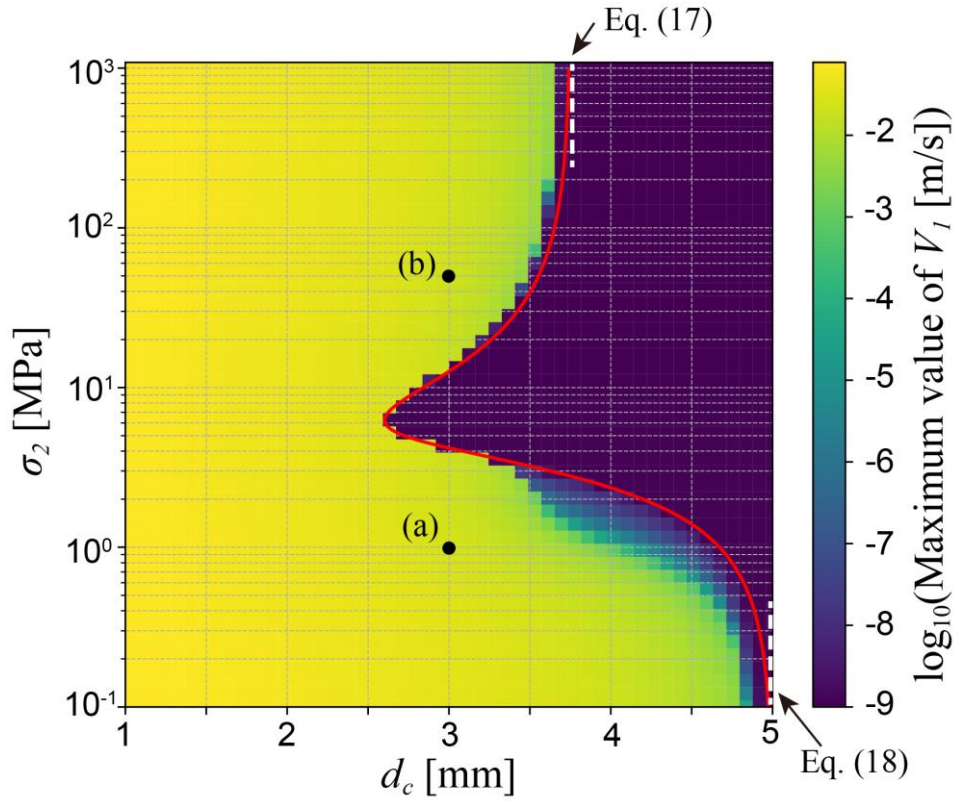
698 VS properties are connected to the driver moving at a constant velocity V_{pl} via springs

699 with stiffness k_d . The two blocks are also coupled to each other by a spring with stiffness

700 k_c . The effective normal stresses σ_1 and σ_2 and shear stresses τ_1 and τ_2 act on the blocks,

701 whose displacements are denoted by x_1 and x_2 , respectively.

702



703

704 Figure 8; *Slip stability of the VW block in the 2DOF model*; The colormap represents the

705 maximum slip velocity of Block 1 (VW block), V_1 , obtained from numerical simulations.

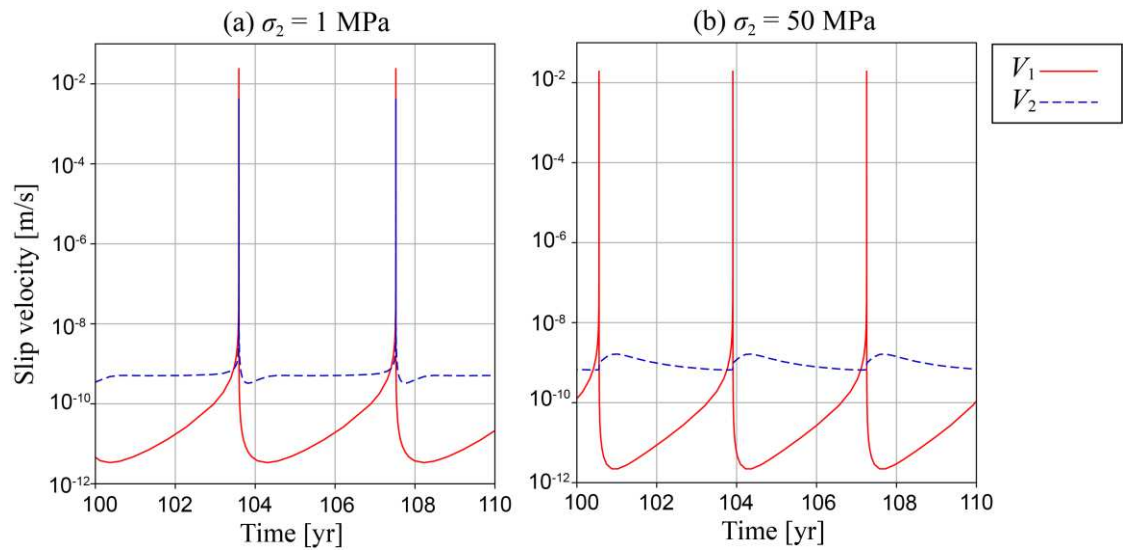
706 The red line represents the stability boundary obtained from linear stability analysis. The

707 white dashed lines represent the asymptotic stability boundaries as σ_2 approaches ∞ or 0

708 (Equations 17 and 18). Points (a) and (b) indicate reference cases for the slip velocity

709 evolution of the blocks shown in Figure 9.

710



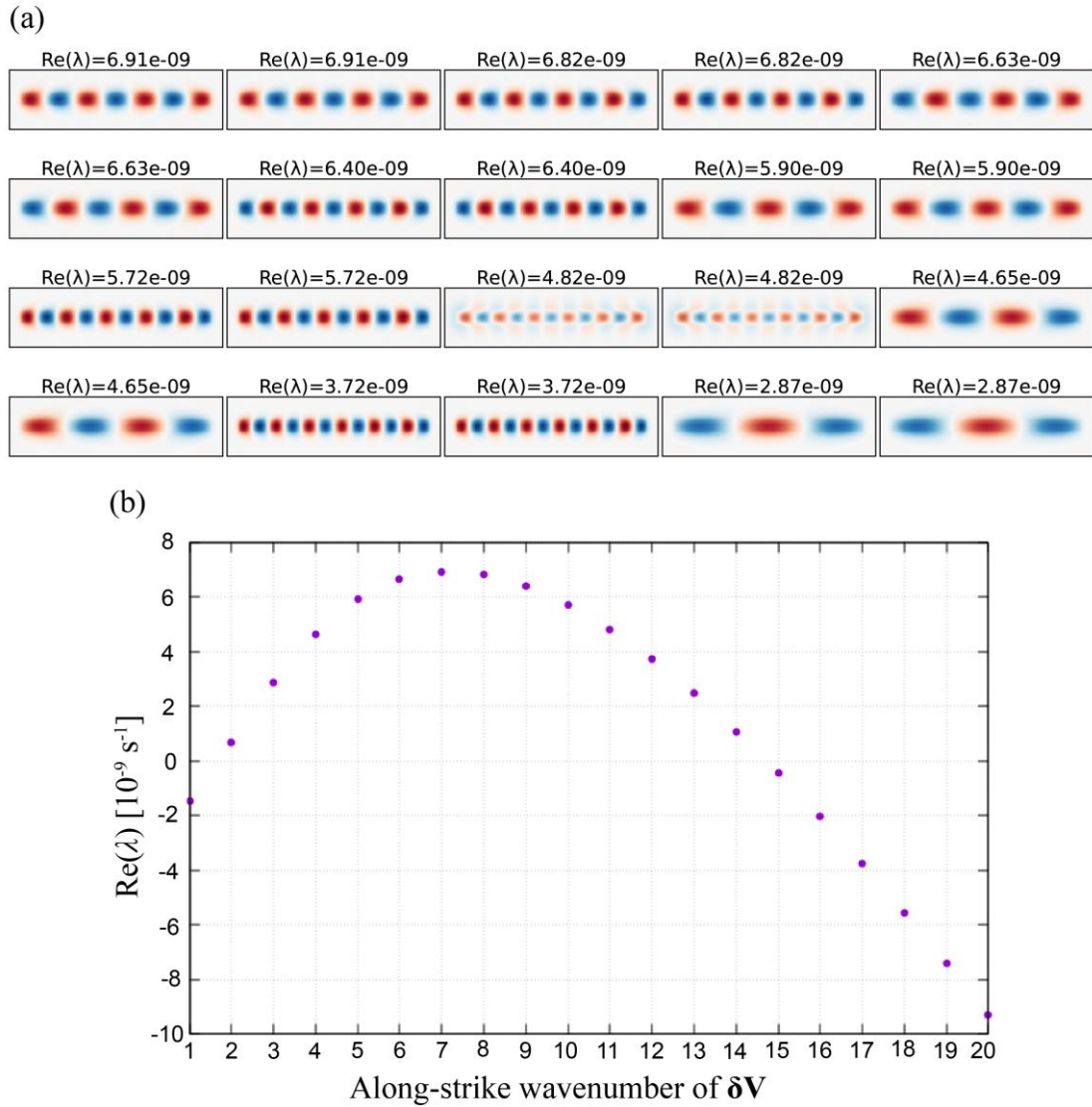
711

712 Figure 9; *Evolution of slip velocity in the 2DOF model*; Slip velocities of the Block 1 (V_1 ;

713 red solid line) and Block 2 (V_2 ; blue dashed line) for cases with σ_2 set to (a) 1 MPa and

714 (b) 50 MPa. d_c is fixed at 3 mm.

715



716

717 Figure 10; *Linear stability analysis of the continuum model with low σ_{VS}* ; (a) Eigenvectors

718 δV for the 20 largest $\text{Re}(\lambda)$. Each panel shows the spatial structure of an eigenvector on

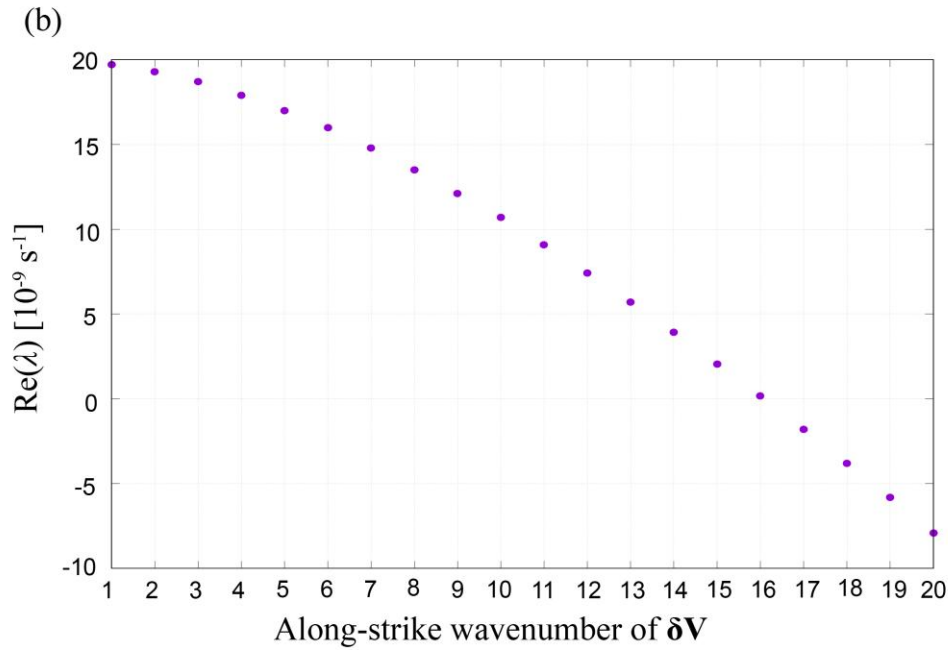
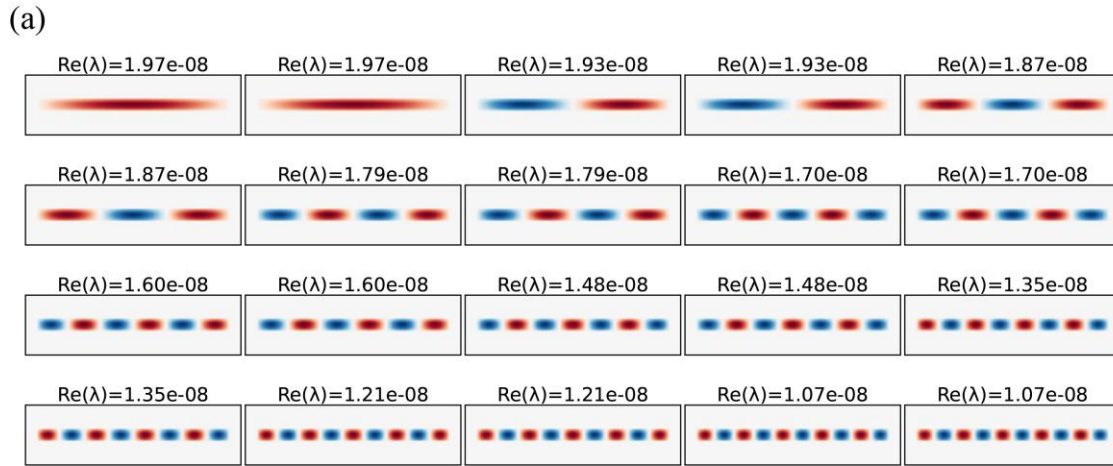
719 the fault plane. Red and blue indicate positive and negative values, respectively. The

720 corresponding value of $\text{Re}(\lambda)$ [s^{-1}] is shown above each panel. Panels exhibiting identical

721 $\text{Re}(\lambda)$ and spatial patterns of δV correspond to conjugate pairs. (b) $\text{Re}(\lambda)$ [s^{-1}] as a function

722 of the along-strike segment number. Conjugate pairs are represented by the same point.

723 The results are obtained for $\sigma_{VS} = 5$ MPa and $d_c = 4.375$ mm.



724

725 Figure 11; *Linear stability analysis of the continuum model with high σ_{VS}* ; Same as Figure

726 10, but for $\sigma_{VS} = 100 \text{ MPa}$ and $d_c = 4.375 \text{ mm}$.

727

Supplementary Files

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- [Graphicalabstract.png](#)