Simulation of slip transients and earthquakes in finite thickness shear zones with a plastic formulation

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We perform numerical experiments of damped quasi-dynamic fault slip that include a rate- and-state behavior at steady state to simulate earthquakes and a plastic rheology to model permanent strain. The model shear zone has a finite width which represents a natural fault zone. Here we reproduce fast and slow events that follow theoretical and observational scaling relationships for earthquakes and slow slip events (SSEs). We show that the transition between fast and slow slip occurs when the friction drop in the shear zone is equal to a critical value, $\Delta \mu_c$. With lower friction drops, SSEs use nearly all of mechanical work to accumulate inelastic strain, while with higher friction drops fast slips use some of the mechanical work to slip frictionally. Our new formulation replaces the state evolution of rate and state by the stress evolution concurrent with accumulation of permanent damage in and around a fault zone.
During an earthquake, elastic strain energy is released as energy carried by seismic waves, kinetic energy released as slip along a frictional interface, energy needed to form new fractures, and thermal energy. For the last two decades, slow slip events (SSEs) have been observed at many subduction zones. Like megathrust earthquakes, SSEs represent shear slip at the plate interface. Unlike fast earthquakes, SSEs are mostly observed through long-term geodetic observations. They are also part of the total energy released through the seismic cycle and since they occur in areas adjacent to the source of very large earthquakes they could potentially load the seismicographic locked patch. SSEs release tectonic stress at lower-frequency than those released by fast earthquakes, likely due to the lower slip and rupture propagation velocities of SSEs. These observations suggest that the elastic energy loaded interseismically is released in fundamentally different ways during SSEs and fast earthquakes. To understand the different slip behaviors of a fault under secular time scales and the interaction between long-term tectonic (LTT) and seismic processes we first need to understand the differences in energy partitioning between fast earthquakes and SSEs. Here we present a first-order attempt at quantifying the partitioning between kinetic and strain energy that are respectively associated with the release of elastic energy in slip and in permanent deformation on fault zones.

There are many numerical studies of the conditions for the emergence of earthquakes and SSEs based on the rate-and-state dependent friction including phenomena such as heat preservation or dehydration reactions. Other attempts model slow slip in viscoelastic media, more adequate for the pressure and temperature conditions under which deep SSEs are observed. Finally, a few attempts at modeling the earthquake cycle in models of LTT deformation use rate and state dependence in viscoplastic formulation of shear zones. The rate and state approach often uses the aging law to describe the time-dependent stickiness or stiffness of two frictional surfaces in contact, allowing for the numerical simulation of earthquakes on predefined fault surfaces. However, the physical meaning of the aging parameter in a shear zone of finite thickness rupturing over multiple surfaces is not fully understood.

Here we develop an approach that considers that aging is the result of the damage history in the fault zone. When the shear zone yields, the incremental accumulation of plastic strain/damage results in incremental changes in shear stress. The stress variations are functions of dynamic friction, μd that is imposed by the rate-dependent friction law at steady state:

\[ \mu_d = \left( \mu_0 + (a-b) \ln \frac{V}{V_0} \right) \]  

where \( V \) is velocity magnitude, \( \mu_0 \) is reference friction coefficient, and \( V_0 \) is reference slip velocity magnitude. \( a \) and \( b \) are dimensionless frictional stability parameters. \( \mu_d \) increases with increasing \( V \) (rate strengthening) if \( a > b \), and \( \mu_d \) decreases with increasing \( V \) (rate weakening) if \( a < b \). Our model shows that the transition between fast and slow transients occurs when \( a-b = -0.0006 \).

**Results**

**Reference model.** To study how the properties of our formulation compare with those of natural slip events, we first test it in an experimental setup similar to a single spring slider system at tectonic scale (Fig. 1a). The 10 km thick upper layer (overriding plate) is elastic. The 2 km thick bottom layer represents the shear zone (where localized fault zones form, e.g., subduction interface). Materials in both layers have same density, bulk, and shear modulus, and cohesion (The values of input parameters are listed in Supplementary Table 1). Fault slip is driven at a boundary velocity of 32 mm yr\(^{-1}\) applied at the top of the model. The sides are free and the bottom is fixed. For simplicity we do not impose any geometrical or rheological heterogeneities in the fault zone (Fig. 1a). The material inside shear zone is uniformly velocity-weakening (\( b-a > 0 \)). Our experimental parameter space includes the fault length, \( L \), and the value of \( b-a \). We vary \( L \) from 20 to 90 km. For each fault length, we run experiments with a different value of \( b-a \) varying from 0.004 to 0.

**Velocity stepping test.** To compare our results with conventional rate-and-state laboratory experiments, we perform a tectonic scale velocity stepping test using our model setup. We first apply a loading rate of 10\(^{-4}\) m s\(^{-1}\) for 3000 years. We then abruptly change the rate to 10\(^{-2}\) m s\(^{-1}\) for about 66 h and drop it back to 10\(^{-4}\) m s\(^{-1}\). We plot the friction coefficient, maximum shear stress, and slip velocity in log scale over displacement during the numerical experiment (Fig. 2a). We remark that the dynamic friction coefficient in the fault zone changes instantaneously when the velocity abruptly increases to 10\(^{-2}\) m s\(^{-1}\). However, the stress change is delayed when compared to the change in slip rate. We also plot the resulting effective friction coefficient (Fig. 2b). This effective or equivalent resulting friction coefficient is calculated by the yield stress (\( \tau_{\text{max}} \cos \phi_b \)) divided by normal stress. Finally, we zoom-in the beginning and ending portions of the period of fast loading. We find that changes in friction coefficient follow a pattern equivalent to the resulting effect of the rate and state aging law. Although we only consider rate-dependent friction in this implementation, the modeled frictional behavior registers both a direct and an evolving effect which are comparable to that of the rate-and-state friction law. In our formulation, the variations in the state of stress (equations 6-11) depend on the deformation history through plasticity (Supplementary Figure 2) and replace the frictional evolution imposed by the aging law.

**Emergence of fast slips and slow transients.** In order to test the properties of our elasto-plastic rate and state formulation, we vary both the length and the \( b-a \) value of the shear zone. As \( b-a \) decreases from 0.004 to 0, slip behavior changes from fast slip transients similar to earthquakes to small creep events (Fig. 3a). Slip instability occurs when the magnitude of the frictional resistive force per unit area, \( F \), decreases faster than the stiffness, \( \kappa \), of the material surrounding the fault as a function of characteristic slip distance, \( \mathcal{L} \). This phenomenon is independent of the evolution law used. This frictional resistive force can be expressed as, \( \Delta F = \Delta \mu \sigma_n \) with the change in friction, \( \Delta \mu = b-a \), and \( \sigma_n \) the normal stress. In our experiments
Scaling relationships. To compare the characteristics of our simulated events to both theoretical and observed scaling relationships, we measured accumulated slip, maximum shear stress, and slip velocity for all simulated events. We identify fast and slow transient events based on their maximum slip velocity, $V_{\text{max}}$. Slow transient events have a maximum slip velocity more than one order of magnitude larger than the background tectonic velocity, and the $V_{\text{max}}$ for earthquakes is of the order of 0.1 m s$^{-1}$ (Fig. 3). We use a plane strain formulation, which means the fault zones are infinitely long in the strike direction. We define the equivalent moment as $M_\text{eq} = DGL \times 4L$. For each event, we measure the duration of slip and use it as the characteristic time to evaluate the scaling relationships.

For slip on a rectangular fault, the stress drop ($\Delta \sigma$) scales linearly with strain change, $\Delta \sigma = CG(D/L)$, where $C = 1^{44}$. We plot the strain drop of the simulated events versus maximum shear stress drop (Fig. 4a). The size of the diamonds represents the length of the modeled fault, $L$, and the color scale shows the value of $a-b$. Filled and unfilled diamonds represent fast and slow transients respectively. Our results show that the stress drop has a dependence on $a-b$ which follows the prediction of the rate and state-dependent friction studies$^{43}$. The stress drop for slow transients is about one order of magnitude smaller than the stress drop for fast earthquakes. Statistically, the results show that the stress drop and strain change scales linearly. Our result also show that stress drop is independent of fault size, which is in good agreement with observations$^{44}$. We also plot co-seismic slips...
events depart substantially from that scaling as relationship between duration and co-seismic slip. However, slow the shear wave speed. The simulated earthquakes follow the linear
variable durations from hours to years, but most plot near or in earthquakes scaling. Slow transients are scattered over very
nearly linearly with

Our results show that SSEs emerge as earthquakes are similar for both fast and slow events.

Discussion

Our results show that SSEs emerge as $a - b$ tends to 0 and that this process is independent of fault size. Slip events simulated by our model follow theoretical scalings and are in general agreement with observations. These scaling relationships emerge from a simplified model setup that does not include any imposed spatial heterogeneities. Our results show that earthquakes and slow transients have different characteristics. In order to understand the processes controlling these differences, we analyze the results from the perspective of the energy spent slipping (kinetic) and that used to damage the shear zone (strain). We calculate the released kinetic, $KE = \rho V^2/2$, and strain energy, $U = \Delta \sigma_1^2 + \sigma_2^2 - 2\mu \sigma_3 + \sigma_3^2 + \sigma_1 \sigma_3)/2E$ per unit volume and define the work efficiency:

$$W_{eff} = \frac{U}{KE + U}.$$

$\rho$, $E$, and $\nu$ are material’s density, Young’s modulus, and Poisson’s ratio and $\sigma_{1,2,3}$ are the principal stresses. For fast transients, $W_{eff}$ decreases to 65% as the fault experiences many episodes of inelastic strain accumulation until $W_{eff}$ abruptly reaches 0% when all the energy is released as slip. For slow transients, $W_{eff}$ is always close to 100% as most of the elastic energy is released in inelastic strain accumulation. Therefore, earthquakes and SSEs differ in the way they partition energy (Fig. 6). Given the transition between fast and slow transients occurred for $\Delta \mu = 0.0006$ for any fault length, $L$, in our model setup (Fig. 3). If $\Delta \mu > 0.0006$, $W_{eff}$ oscillates between ~98 and 65%, which for the fast slip the fraction of kinetic energy increases to 35% in bursts (Fig. 6a). After the earthquake is only kinetic as slip velocity decreases to tectonic velocity. If $\Delta \mu < 0.0006$, most of the work done is damaging the fault zone. The incremental nature of the change in $W_{eff}$ is related to the fact that the Mohr Coulomb formulation decreases friction and accumulate strain in increments. Before any event the fault is yielding and creeps plastically. The observed transition in energy partitioning coincides with $\gamma = 1$. For an earthquake $\gamma > 1$ and the energy exceeding the deformation potential of the fault zone is used to accumulate frictional slip (Kinetic Energy) and is likely dissipated as heat in a

Fig. 2  Velocity stepping test. a Friction coefficient, maximum shear stress, and velocity against displacement. Rate-dependent friction shows the direct response to the velocity change. The maximum shear stress also changes but with delay. b Calculated equivalent resulting effects. The resulting effect has an instantaneous increase followed by a gradual decrease. c Direct, evolving, and resulting frictional effect of the rate-and-state-dependent friction law

against durations (Fig. 4b). For earthquakes, the duration $T$ needed for slip to reach its maximum value at any point along the fault is predicted to be $T = G \cdot D/(V_{shear} \cdot \Delta \sigma)$, where $V_{shear}$ is the shear wave speed. The simulated earthquakes follow the linear relationship between duration and co-seismic slip. However, slow events depart substantially from that scaling as $D \sim T^{1/2}$.

Finally, we plot $T$ for all fast and slow transients versus $M_0$ (Fig. 5). Ide, et al. proposed scaling relationships for both fast and slow earthquakes. For slow earthquakes, $M_0$ scales with $T^3$. The simulated fast slips are following the proposed fast earthquakes scaling. Slow transients are scattered over very variable durations from hours to years, but most plot near or in the proposed slow transients scaling. We also compare the results with observations complied by Peng and Gomberg. The duration versus moment distribution of the numerical results from our study and the observations of subduction zone earthquakes are similar for both fast and slow events.

Discussion

Our results show that SSEs emerge as $a - b$ tends to 0 and that this process is independent of fault size. Slip events simulated by our model follow theoretical scalings and are in general agreement with observations. These scaling relationships emerge from a simplified model setup that does not include any imposed spatial heterogeneities. Our results show that earthquakes and slow transients have different characteristics. In order to understand the processes controlling these differences, we analyze the results from the perspective of the energy spent slipping (kinetic) and that used to damage the shear zone (strain). We calculate the released kinetic, $KE = \rho V^2/2$, and strain energy, $U = \Delta \sigma_1^2 + \sigma_2^2 - 2\mu \sigma_3 + \sigma_3^2 + \sigma_1 \sigma_3)/2E$ per unit volume and define the work efficiency:

$$W_{eff} = \frac{U}{KE + U}.$$

$\rho$, $E$, and $\nu$ are material’s density, Young’s modulus, and Poisson’s ratio and $\sigma_{1,2,3}$ are the principal stresses. For fast transients, $W_{eff}$ decreases to 65% as the fault experiences many episodes of inelastic strain accumulation until $W_{eff}$ abruptly reaches 0% when all the energy is released as slip. For slow transients, $W_{eff}$ is always close to 100% as most of the elastic energy is released in inelastic strain accumulation. Therefore, earthquakes and SSEs differ in the way they partition energy (Fig. 6). Given the transition between fast and slow transients occurred for $\Delta \mu = 0.0006$ for any fault length, $L$, in our model setup (Fig. 3). If $\Delta \mu > 0.0006$, $W_{eff}$ oscillates between ~98 and 65%, which for the fast slip the fraction of kinetic energy increases to 35% in bursts (Fig. 6a). After the earthquake is only kinetic as slip velocity decreases to tectonic velocity. If $\Delta \mu < 0.0006$, most of the work done is damaging the fault zone. The incremental nature of the change in $W_{eff}$ is related to the fact that the Mohr Coulomb formulation decreases friction and accumulate strain in increments. Before any event the fault is yielding and creeps plastically. The observed transition in energy partitioning coincides with $\gamma = 1$. For an earthquake $\gamma > 1$ and the energy exceeding the deformation potential of the fault zone is used to accumulate frictional slip (Kinetic Energy) and is likely dissipated as heat in a
natural system. For SSEs, $\gamma > 1$ and most of the elastic energy available is used to deform the fault zone plastically and creep. Our results therefore depart from the existing rate-and-state numerical studies that assign the emergence of slow earthquakes to processes by reducing the ratio of fault length to nucleation length. We now use the equivalent ratio $\gamma$ and assign a physical meaning to the emergence of SSEs or earthquakes that corresponds to the energy partitioning between frictional slip and damage in a fault zone of finite thickness. Our formulation in DynEarthSol3D (DES3D) is also highly flexible and can be used

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**Fig. 3** Emergence of fast slips and slow transients. **a** Slip mode transition on models with 60 km fault length and different $a-b$ values. **b** Slip behavior for different fault lengths and $a-b$ values. The scale bar shows the ratio between number of earthquakes and slow transient events. Yellow: the model only generates earthquakes. Blue: the model only generates creeping events.

**Fig. 4** Seismic scaling relationships. **a** Relationship between strain change and stress drop. For fast and slow transient events strain drop generally scale linearly (dashed lines) with stress drop. Observations show that stress drop is independent of fault size. Within the linear dependence our results agree with observations. **b** Scaling relationship between co-seismic slip and duration. Duration of simulated earthquakes scales linearly with co-seismic slip. However, slow transient departs widely from this scaling. Filled diamonds: earthquake events. Unfilled diamonds: slow transients. The size of the diamonds represents the length of the modeled fault, $L$, and the color scale shows the value of $a-b$, from 0 (yellow) to −0.004 (blue).
to study the emergence of SSEs and megathrust earthquakes at rough or smooth subduction interfaces of finite thickness under varying pore fluid pressure conditions. For example, subduction zones with weak fault zones are thought to be the locus of large earthquakes while strong and rough interfaces are thought to be the locus of smaller events (i.e., Southern Chile vs Hikurangi).

Our experiments and the slip instability condition suggest that fault zones composed of weak material with low shear modulus could indeed the locus of large earthquakes and strong or rough material can lead to the emergence of slow earthquakes. However, if \( b-a \) is close to zero and smaller than \( \Delta \mu_c \), weak sediments with low fluid pore pressure will always lead to slow transients or creep events. On the other hand, if \( b-a \) is larger than \( \Delta \mu_c \), megathrust earthquakes may occur with a rough and strong basaltic oceanic crust under high pore fluid pressure.

**Methods**

**DES3D and fast lagrangian analysis of continua (FLAC).** At present, the most used formulation of rock friction is provided by the empirical rate-and-state dependent friction relationship. This framework considers the characteristic properties of fault surface including slip distance, slip velocity, normal stress, and state variables. However, this model does not include mechanisms such as fracturing during fault formation and evolution over tectonic time scales. Processes including fault damage, formation, and material properties evolution are accounted in LTT geodynamics models such as DynEarthSol2D (DES2D) and DynEarthSol3D (DES3D is developed from DES2D). DES3D is a robust, adaptive, multi-dimensional, finite element method. It solves the momentum and energy conservation equations in Lagrangian form using...
unstructured meshes. It uses the explicit FLAC algorithm to solve for momentum balance. This approach solves the dynamic problem, \( \nabla \sigma_i + \rho C_0 \delta \varepsilon = \rho \dot{u}_i \), for quasi-static equilibrium, \( \nabla \sigma_i = \rho C_0 \delta \varepsilon = 0 \) in LTT models. \( i \) and \( j \) correspond to element wise and \( n \) to nodal wise quantities. Where \( \rho \), \( \sigma \), \( a \), and \( \varepsilon \) are density, Cauchy stress tensor, nodal acceleration, and strain accumulation and slip events we use a Mohr-Coulomb plasticity formulation of rate-dependent friction. History dependent plasticity is a constitutive relationship (rheology). Time steps are calculated with \( \Delta t = \frac{\text{bulk modulus of the material}, K}{\rho \text{max}} \), which satisfies the Courant–Friedrichs–Lewy condition explicit time step. \( \Delta t_{\text{min}} \) is the minimum length (smallest grid size) of the whole mesh. Supplementary Figure 1 illustrates the flow of the FLAC algorithm.

**History dependent plasticity.** In order to simulate fault formation by inelastic strain accumulation and slip events we use a Mohr-Coulomb plastic formulation that includes a yield stress, a plastic flow law, and a friction law (Eq. 1). A shear zone forms as strain localizes when elastic stresses exceed yield stress interseismically and can further accumulate when the dynamic friction \( \mu_d \) changes as a function of velocity during a slip event.

For each time step, in a given element of the fault zone and in the frame of reference of the principal stresses, the strain increments are given by \( \Delta \varepsilon = \frac{\Delta t}{\lambda + \beta} \), and \( \Delta \varepsilon = \frac{\Delta t}{\lambda + \beta} \), and \( \Delta \varepsilon = \frac{\Delta t}{\lambda + \beta} \), and \( \Delta \varepsilon = \frac{\Delta t}{\lambda + \beta} \), where \( \lambda \) and \( \Gamma \) are Lame parameters. The element is in failure if the shear stress exceeds the Mohr-Coulomb yield criterion. If the state of stress is containing within the yield stress envelope the fault zone continues loading elastically up to what is observed in laboratory experiments. Within the yield stress envelope the fault zone continues loading elastically. In order to simulate fault formation by inelastic strain accumulation and slip events we use a Mohr-Coulomb plasticity formulation of rate-dependent friction. Time steps are calculated with \( \Delta t = \frac{\text{bulk modulus of the material}, K}{\rho \text{max}} \), which satisfies the Courant–Friedrichs–Lewy condition explicit time step. \( \Delta t_{\text{min}} \) is the minimum length (smallest grid size) of the whole mesh. Supplementary Figure 1 illustrates the flow of the FLAC algorithm.

\[
\begin{align*}
\nabla \sigma_i + \rho C_0 \delta \varepsilon = \rho \dot{u}_i, \\
\Delta t = \frac{\text{bulk modulus of the material}, K}{\rho \text{max}}, \\
\Delta t_{\text{min}} = \frac{\text{minimum length (smallest grid size) of the whole mesh}}{\rho \text{max}}.
\end{align*}
\]

\( K \) is the bulk modulus of the material, \( \rho\delta \) is a fictitious scaled density, and \( c \) is an empirical constant in the order of \( 10^8 \). By solving Eqs. (3–5) each time step, we obtain new nodal velocities and displacements. We can then update the state of stress by loading the element elastically:

\[
\sigma_{i+1}^{\text{elastic}} = \sigma_i + (\lambda + 2\mu) \Delta \varepsilon + \lambda \Delta \varepsilon_i,
\]

where \( \lambda \) and \( \mu \) are the corrected principal stresses. \( \Delta \varepsilon = (\lambda + 2\mu) \Delta t / (\lambda + \mu) \), and \( \Delta \varepsilon = (\lambda + 2\mu) \Delta t / (\lambda + \mu) \), where \( \lambda \) and \( \Gamma \) are Lame parameters. The element is in failure if the shear stress exceeds the Mohr-Coulomb yield criterion. If the state of stress is containing within the yield stress envelope the fault zone continues loading elastically up to what is observed in laboratory experiments.

**Implementations for slip events.** In order to simulate tectonic processes across time scales, depart from LTT DES3D, we apply adaptive time-stepping technique. Our simulation uses a second order explicit time-stepping algorithm for integration. The time step scales inversely to the maximum slip velocity magnitude, \( v_{\text{max}} \), in the model, \( \Delta t = \min \left( \frac{1}{\sqrt{\rho}}, \frac{1}{C_0} \right) \). We use \( c = 10^5 \) in this paper. When the maximum slip velocity reaches the shear velocity \( \sqrt{G/\rho} \approx 400 \text{ km s}^{-1} \), we use the minimum time step, \( \Delta t_{\text{min}} = \min \left( \frac{1}{\sqrt{\rho}}, \frac{1}{C_0} \right) \). Therefore, in this study, \( \Delta t = \min \left( \frac{1}{\sqrt{\rho}}, \frac{1}{C_0} \right) \), and \( \rho_{\text{max}} = \frac{\text{minimum length (smallest grid size) of the whole mesh}}{\rho \text{max}} \), the peak slip velocity of our simulated earthquake can reach to shear wave speed (Supplementary Figure 3b).

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Author contributions
X.T. performed experiments and analyzed the data, L.L.L. supervised the PhD student. X.T. and L.L.L. designed the numerical method and research path.

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