Spontaneous aseismic and seismic slip on evolving faults in a continuum-mechanics framework

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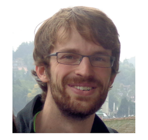

Robert Herrendörfer*, Ylona van Dinther , and Taras Gerya
Institute of Geophysics, ETH Zurich, Switzerland
* robert.herrendoerfer@erdw.ethz.ch

1. Objectives and summary

Numerical model of spontaneous slip transients in subduction zones:
tool to investigate links between permanent deformation and slip transients

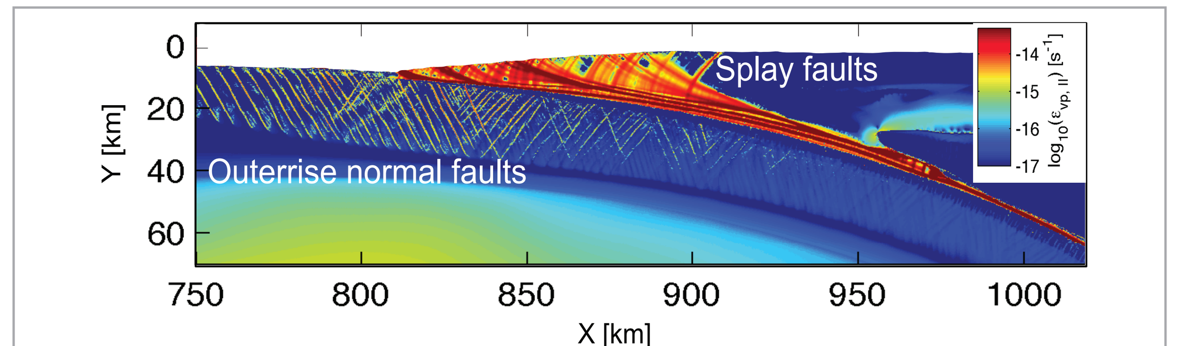

Figure 1: Strain rates in a large-scale simulation, indicating the location of the megathrust as well as differently oriented splay and outerrise normal faults (Van Dinther et al., 2013b)

Continuum mechanics
Visco-elasto plastic rheology
so far : rate-dependent friction
On- and off megathrust events

Gerya and Yuen, 2007, Van Dinther et al., 2013a,b, 2014

\+ Implementation of

new: a) rate- and state-dependent friction (RSF) b) adaptive time stepping (Lapusta et al, 2000)
c) fault evolution: strain weakening of cohesion

Can realistic seismic and aseismic transients on and off the megathrust be simulated in a continuum model?

We have implemented an invariant rate-and state-dependent friction (RSF) formulation and adaptive time stepping in a continuum mechanics framework (section 2). In a subduction zone model with a predefined megathrust (section 3), we simulate a response spectrum from stable sliding, periodic slow slip events, and seismic events, which is in general agreement with theoretical estimates of the nucleation size and numerical simulations by Liu and Rice (2007) (Figure 4). Seismic slip rates are reached (Figure 5), but are currently under-resolved in order to model multiple seismic events.
The application of rate-and state dependent friction in the entire, cohesionless upper plate results in a different fault orientation (section 4). Deformation localizes only for rate-weakening friction for RSF parameter within the lab range. **On these spontaneously developing rate-weakening faults, stable sliding or aseismic and seismic slip transients spontaneously occur.** Stronger localization of deformation and slower fault evolution is achieved through **strain weakening of cohesion** (section 5). Currently, we are investigating the transition between strain weakening and rate-and state dependent friction.

2. Implementation of **invariant** RSF in a continuum mechanics framework

Conventional RSF formulation

(Dieterich, 1978, 1979, Ruina, 1983)

fault --> predefined planar interface

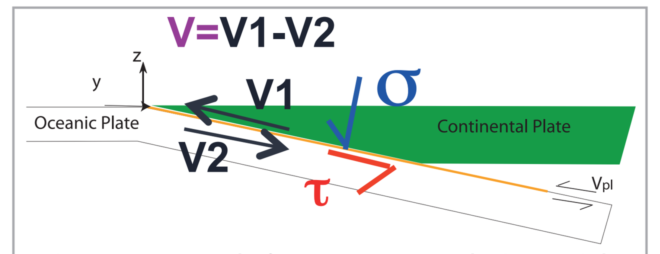

Figure 2: Example for a conventional RSF model setup, adapted from Liu and Rice (2007).

$$\mu = \mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{\theta}{\theta_0}\right) \qquad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

$$\tau = a\sigma \operatorname{arcsinh}\left[\frac{V}{2V_0}\exp\left(\frac{\mu_0 + b\ln(\frac{\theta V_0}{L})}{a}\right)\right]$$

Continuum mechanics approach:

Solve for velocity and pressure fields:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \qquad \frac{\partial \sigma'_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} - \frac{\partial P}{\partial x} = \rho\frac{Dv_x}{Dt} - \rho g_x \qquad \frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma'_{yy}}{\partial y} - \frac{\partial P}{\partial y} = \rho\frac{Dv_y}{Dt} - \rho g_y$$

enters into:

Visco-elasto-plastic constitutive relationship:

$$\sigma'_{ij} = 2\eta_{vp} Z \dot{\varepsilon}'_{ij} + \sigma'^{old}_{ij}(1-Z), \qquad Z = \frac{G\Delta t_{comp}}{G\Delta t_{comp} + \eta_{vp}}$$

Visco-plastic viscosity:

$$\eta_{vp} = \min\left[\eta_v, \eta_p = \frac{\sigma_{yield}}{2\dot{\varepsilon}'_{II(vp)}}\right]$$

Yield strength:

$$\sigma_{yield} = C + \mu P$$

new: invariant formulation of RSF:

replacement of slip velocity, normal and shear stress by invariant variables:

$$V = 2\,\dot{\varepsilon}'_{II(p)}dx$$

$$\frac{d\theta}{dt} = 1 - \frac{2\,\dot{\varepsilon}'_{II(p)}dx \cdot \theta}{L}$$

$$\sigma'_{II} = \sigma'_{yield} = aP \operatorname{arcsinh}\left[\frac{\dot{\varepsilon}'_{II(p)}}{2\dot{\varepsilon}'^{0}_{II(p)}}\exp\left(\frac{\mu_0 + b\ln\left(\frac{\theta\, 2\dot{\varepsilon}'^{0}_{II(p)}dx}{L}\right)}{a}\right)\right]$$

fault --> spontaneously developing shear zone

3. Stability analysis: response of a predefined fault to tectonic loading

Model setup:

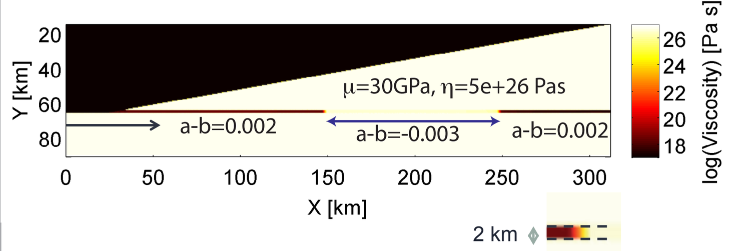

Figure 3: Model setup: In section 2, RSF is applied only in a layer of 2 km between upper and lower plate. In section 3, RSF is applied in the entire upper plate.

Model simplifications:
1) constant pressure P in RSF equations
2) RSF is applied in frictional boundary layer (2km width) only

Response spectrum shown in Liu and Rice (2007) (Fig. 4b):

Stability transitions depend mainly on the ratio between fixed size of the seismogenic zone W and the nucleation size h* for a given depth-dependent distribution of a and b.

We aim to validate our implementation of rate-and state dependent friction by qualitatively comparing our response spectrum (Fig. 4a) to that given in Liu and Rice (2007) (Fig. 4b).

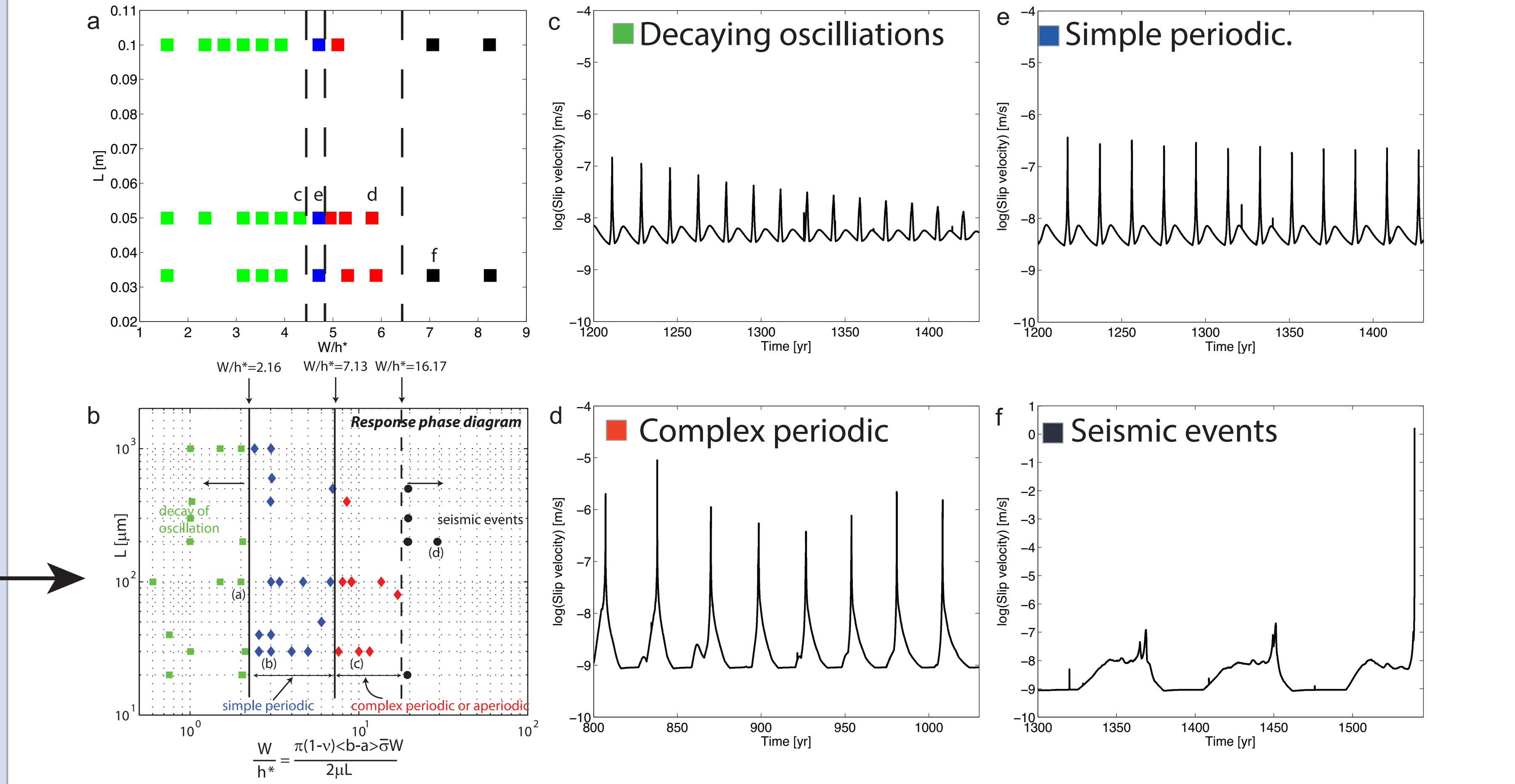

Figure 4: (a) Response spectrum this study **(b)**, response spectrum in Liu and Rice (2007), **(c-f)** examples of responses in this study.

We observe a similar transition from decaying oscillations, simple periodic, complex periodic to seismic events.

Discussion

1) Stability transitions do not depend only on W/h inside the rate-weakening zone, but also on the rest of the model setup, such as the friction parameter of the adjacent rate-strengthening regions. Therefore, differences in the model setup make a direct comparison to Liu and Rice (2007) difficult.

2) We expect a wider range of simple periodic oscillations (Figure 4). We will further improve our implementation.

3) In the model reaching seismic slip rates, we observe the generation and propagation of waves (Fig. 5). However, current spatial resolution (grid size=500m) is too low by a factor of 2 to fully resolve the cohesive zone during seismic rupture propagation.

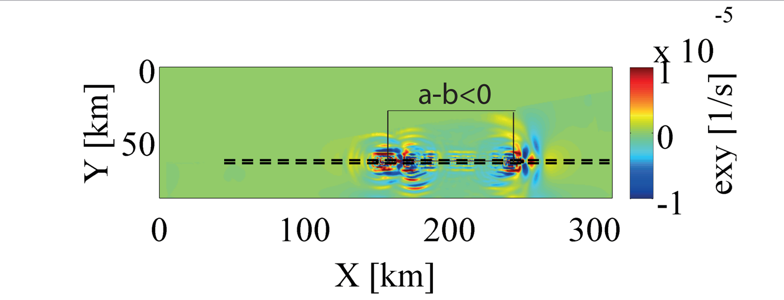

Figure 5: Shear strain rates during seismic wave propagation.

4. Spontaneous off-megathrust faults and slip transients

To study slip transients beyond the megathrust, we apply rate-and state-dependent friction also in the entire, **cohesionless** upper plate (i.e. C=0 Pa). Below, we vary the RSF parameters a and b inside the upper plate.

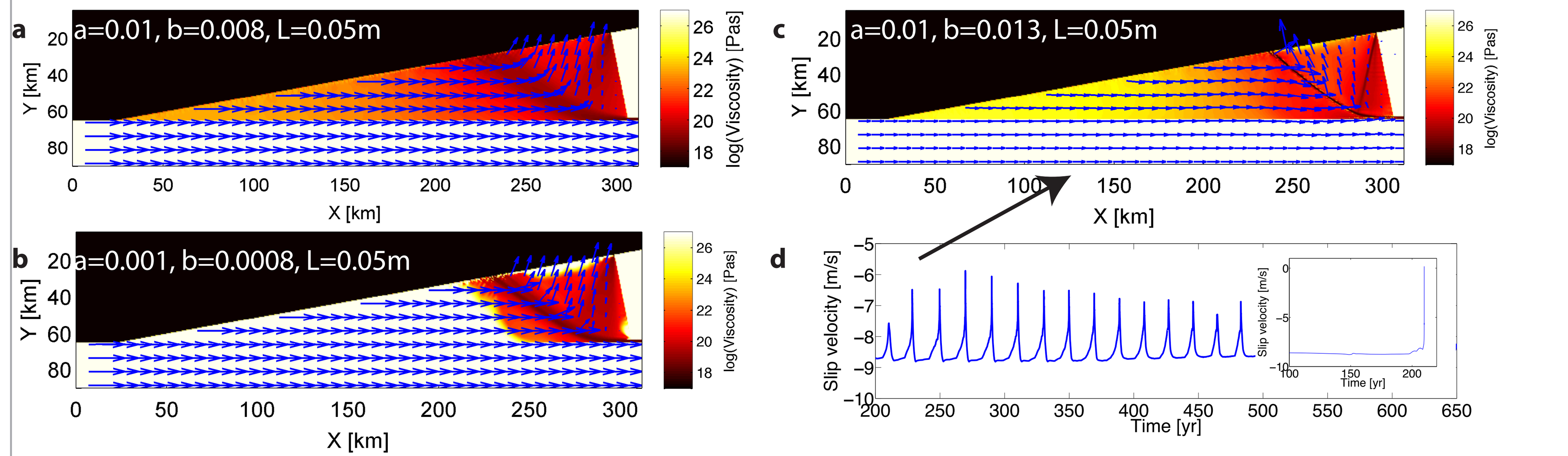

Figure 6: (a-b), Visco-plastic viscosity for **(a-b)** rate-strengthening and **(c)** rate-weakening friction. **(d)**Time series of slow events in **(c)**, inlet shows seismic event.

Does deformation localize under rate-strengthening and rate-weakening friction in the upper plate?
Sometimes. A fault-like shear band develops with a significantly different orientation than the predefined fault in section 3 (Fig. 3).
On a rate- strengthening fault, deformation is rather diffuse for RSF parameters inside the lab range (Figure 6a), while stronger localization appears for RSF parameters outside of the lab range (Figure 6b). **Strong localization of deformation occurs for realistic RSF parameters in case of rate-weakening friction (Fig. 6b).**

Do slip transients occur spontaneously?
Yes. **Slow slip (Fig. 6b) and seismic events (Fig. 6b, inlet, higher mean stress P) occur spontaneously on these newly formed rate-weakening fault zones (Fig. 6d).** For different RSF parameters (e.g., lower mean stress P), stable sliding occurs.

5. Long-term fault evolution

In section 4, we assume an initially cohesionless material. As a consequence, the fault development is very fast and the deformation only localizes to some degree. **To introduce permanent weakening of the material during the brittle fault formation process, and thereby to bridge long and short timescales, we model linear weakening of cohesion C with integrated plastic strain** γ (Lavier et al, 2000):

new:

$$C = C_0\left(1 - \frac{\gamma}{\gamma_0}\right), C = 0\ \mathrm{Pa} \quad \text{for} \quad \gamma \geq \gamma_0$$

- Cohesion reduces from initial cohesion C_0 to 0 Pa at critical plastic strain γ_0.
- At $\gamma=\gamma_0$, the fault is considered mature and rate-and state dependent friction is locally applied.
- **Deformation strongly localizes in the fault formation phase, during which cohesion is reduced (Fig. 6a,b).**

- Transition between long-term strain-weakening and short-term rate-and state friction and different time scales?
  - computation of state evolution for *L**
  - evolution of *L** with plastic strain towards *L* (motivated by Marone and Kilgore,1993):

new:

$$L^* = L^c - \frac{\gamma}{\gamma_0}(L^c - L), L^c = 2\gamma_0\Delta x, \quad L^* = L \quad \text{for} \quad \gamma \geq \gamma_0$$

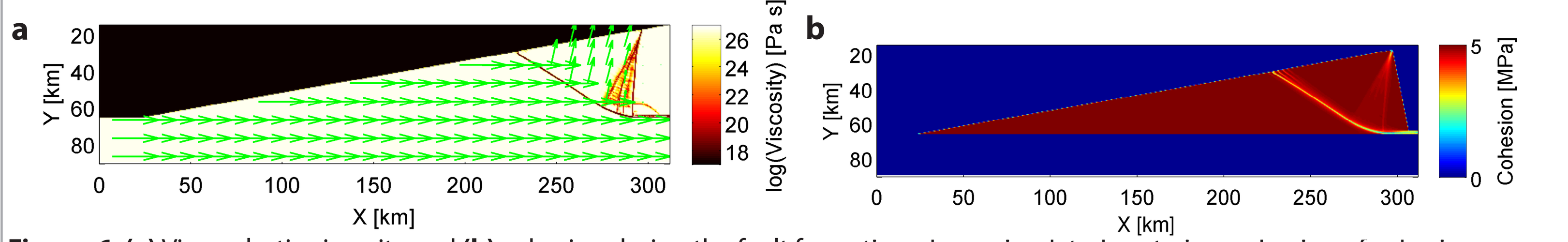

Figure 6: (a) Visco-plastic viscosity and **(b)** cohesion during the fault formation phase, simulated as strain weakening of cohesion.

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