From millions of years to sub-second time scales in subduction earthquake sequence models: linking slab, mantle and surface displacements.

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Objective

To cross time scales from millions of years to sub-seconds by using an invariant reformulation of rate- and state-dependent friction in a heterogenous subduction zone to unravel the link between slab, mantle and surface displacements.

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Method

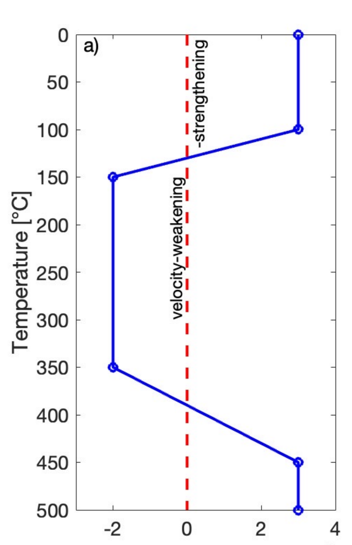
We extend geodynamic [1] and seismo-thermo-mechanical [2] codes, which solve conservation of momentum, continuity and energy for a visco-elasto-plastic material.

In the short-term we extend a non-associated plastic flow law with an invariant formulation of the rate- and state-dependent friction [3]

$$\tau_{II} = \sigma_{yield} = \sigma_c + \arcsin\left[\frac{V_p}{2V_0}\exp\left(\frac{b}{a}\ln\left(\frac{\Theta V_0}{L}\right)+\frac{\mu_0}{a}\right)\right] aP$$

Times are resolved using an adaptive time stepping scheme [3]:

$$\Delta t = \zeta min_{n_x=1,n_y=1}^{N_x,N_y}\left[min\left[\Delta t_w, \Delta t_h, \Delta t_d, \Delta t_{vep}\right]\right]$$



7 rock types are used (Fig. 1). The oceanic crust has a fractured and hydrated upper crust with temperature dependent velocity weakening and cohesion.

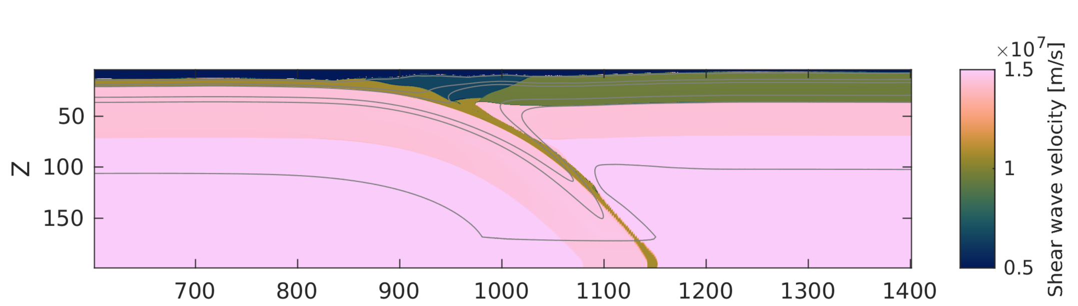


Fig 1. Impediance contrast after 4 Myr of subduction.

Result: Earthquake

- Simulation of two slow slip events followed by an earthquake with a maximum slip rate of 6.3 m/s (Fig 2,3& 5)
- Coseismic period is resolved with more than 2000 timesteps, which go down to $4 * 10^{-3}$ sec. (Fig 3)

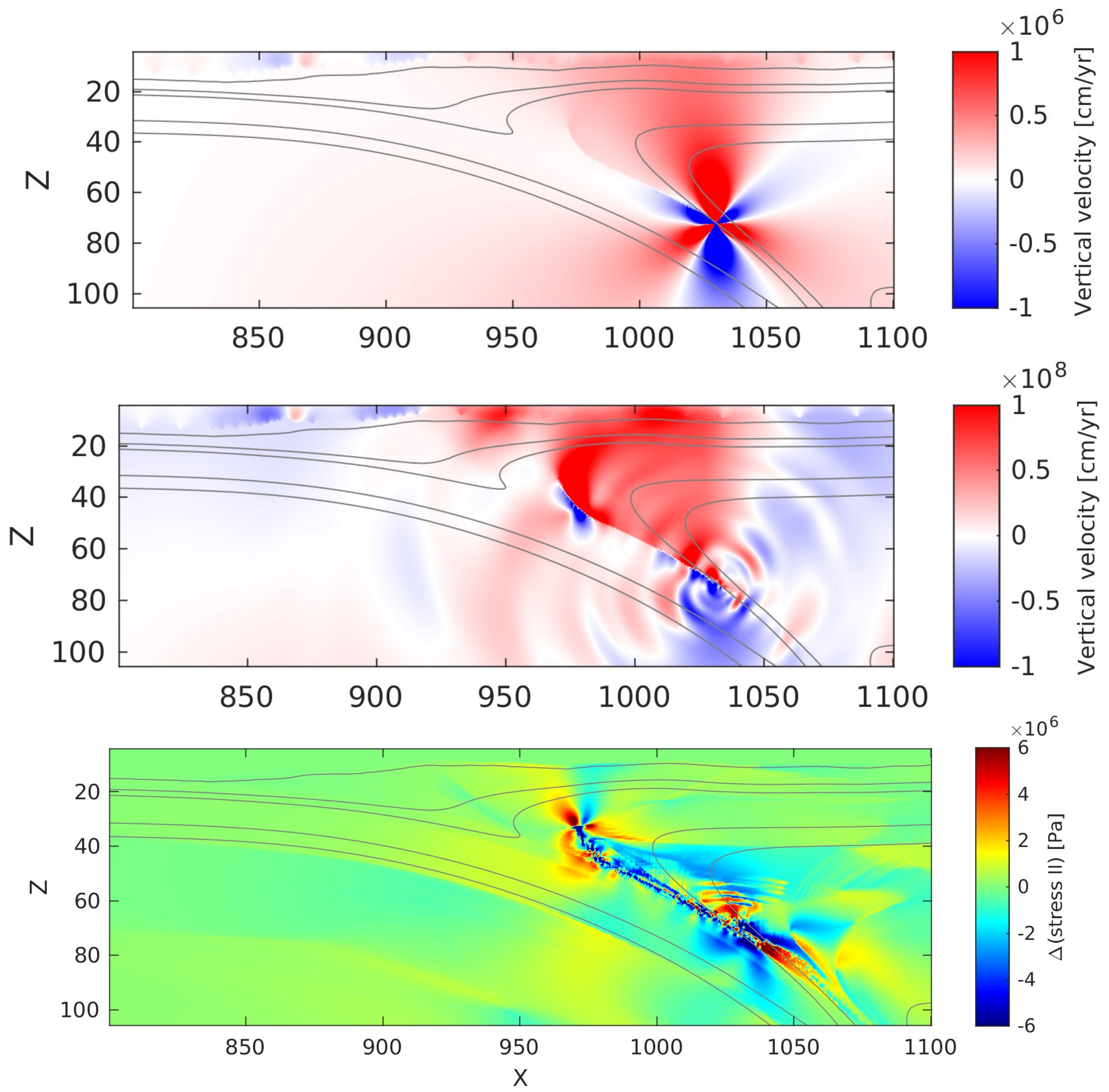


Fig 2. Vertical velocity during the nucleation (top) and propagation (middle) of the earthquake. Bottom change in stress at the end of the earthquake.

- Uplift is 2.2 m in the coseismic period (Fig. 4)
- Waves reflect from the impedance contrast at the updip limit and at the downdip limit of the velocity weakening. (Fig. 5)

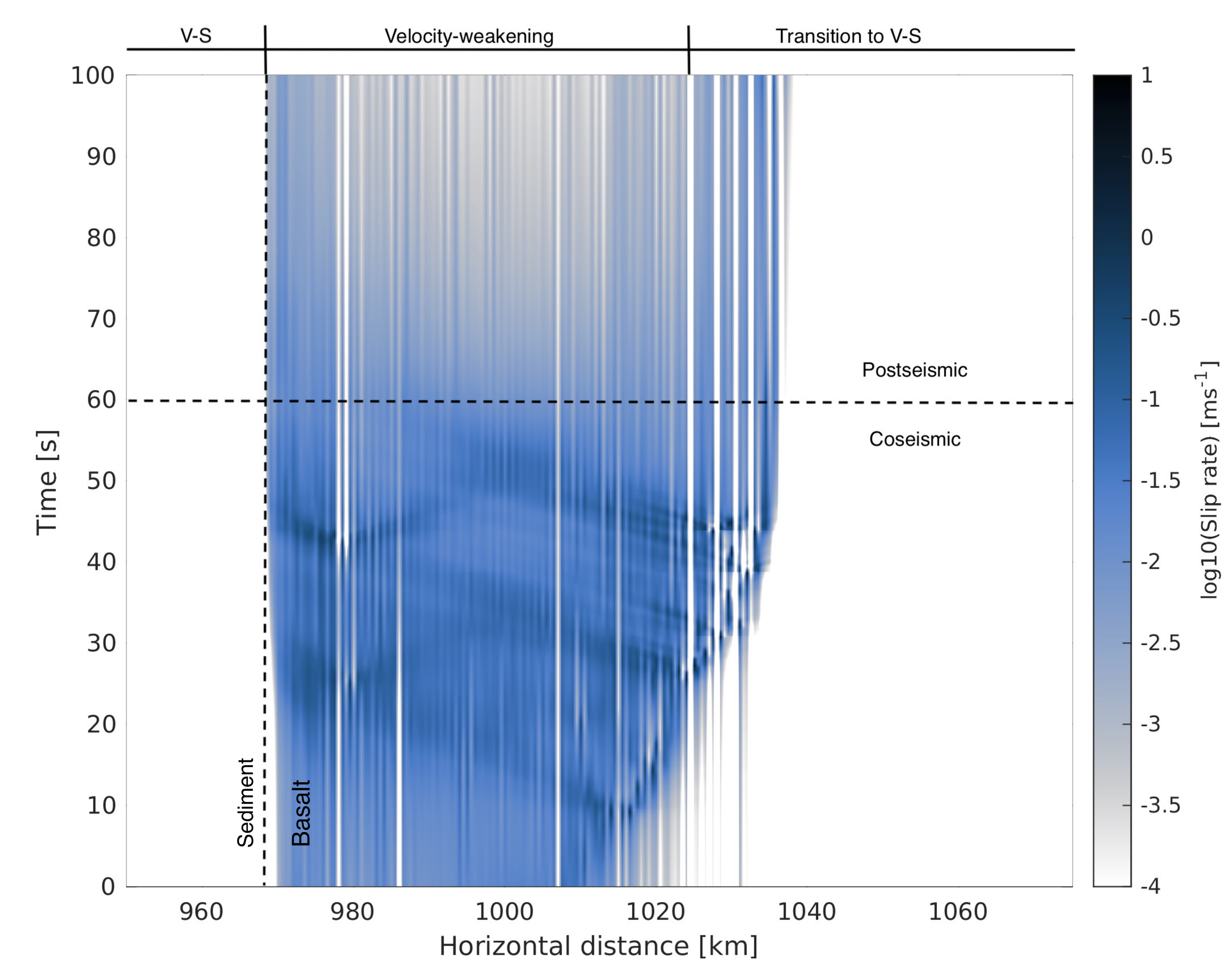


Fig 5. Slip rate evolution with time in the fault zone.

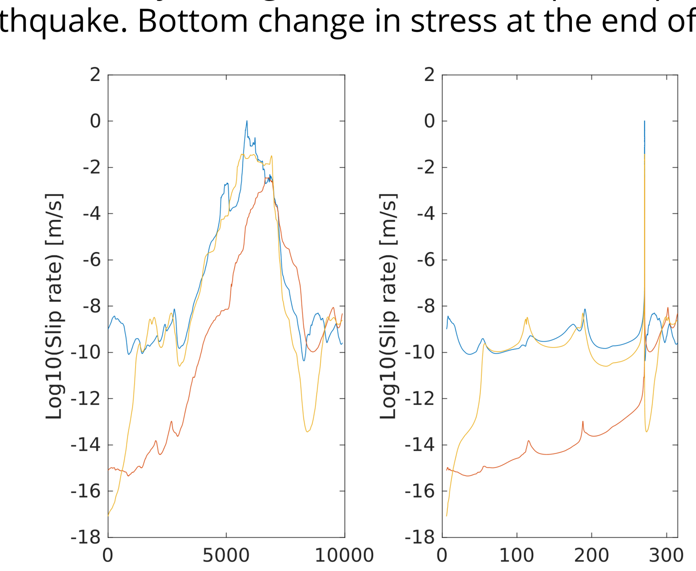


Fig 3. Slip rate on three nodes on the fault zone per time step (left) and per abosolute time (right).

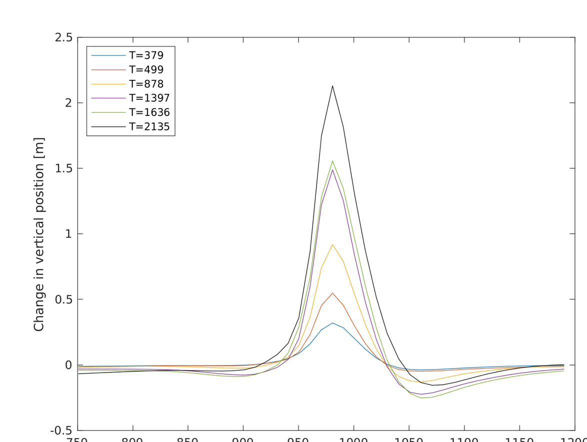


Fig 4. Vertical surface displacement during the coseismic period. Postive change is upward movement and lines indicate different timesteps.

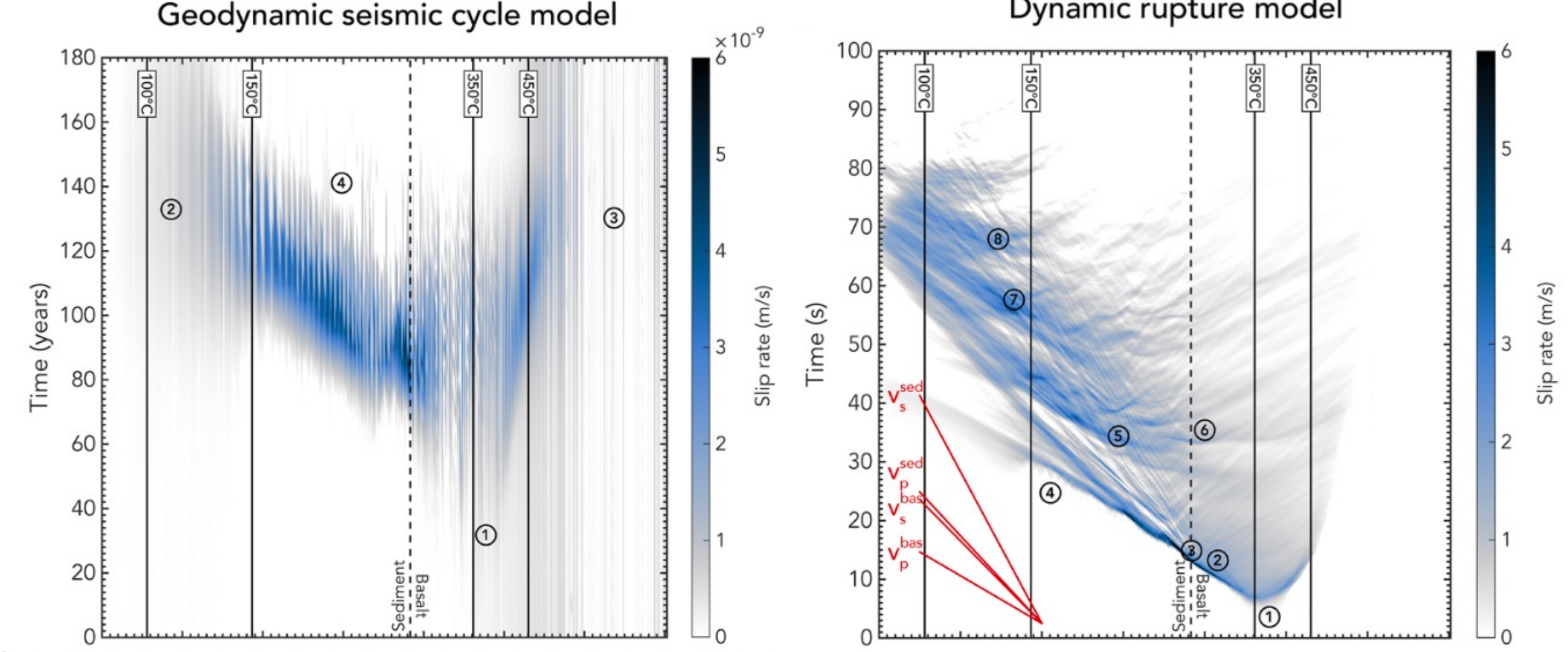


Fig 6. Slip rate evolution with time for the geodynamic seismic model (left) and the dynamic rupture model (right) [4].

Model behaviour

- Model behaviour is characterised by four regimes:
  1. Stable sliding (Fig. 7.1)
  2. Periodic slow slip (Fig. 7.2)
  3. Slow slip and one earthquake (Fig. 7.3)
  4. Slow slip events and multiple earthquakes. (Fig 7.4)
- Resembles regimes of Liu and Rice (2007) [5].

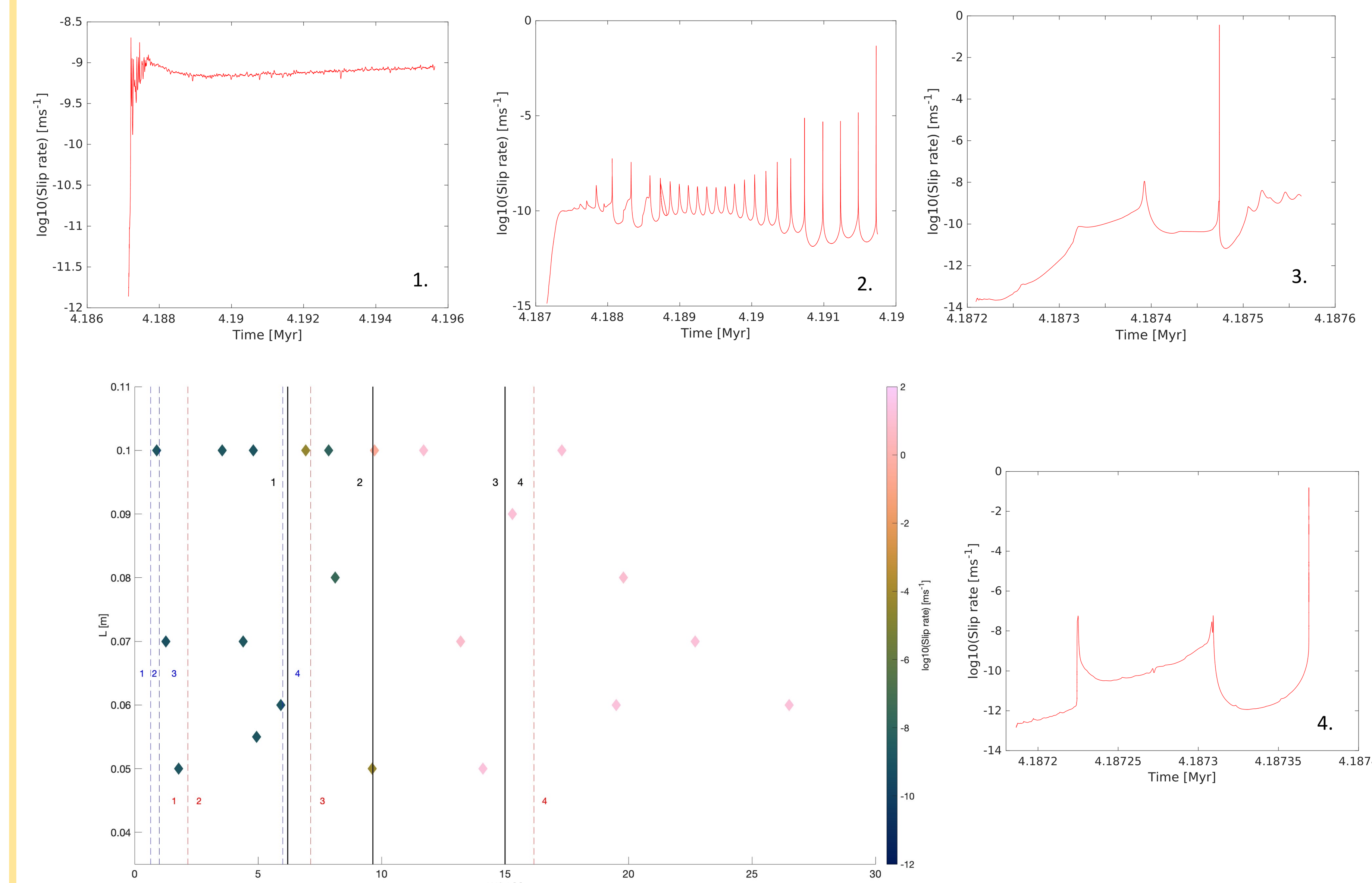


Fig 7. Slip spectrum as a function of nucleation size with black lines indicating different regimes of our study, red dotted lines of Liu & Rice (2007) [5] and blue dotted lines of Herrendörfer et al. (2018) [3]. Four surrounding figures give slip pattern of the regimes.

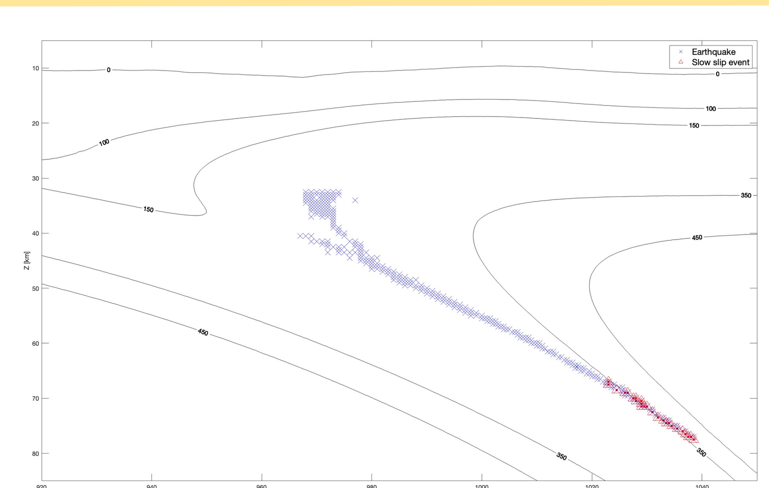


Fig 8. Location of slipping nodes for earthquake (blue) and for the slow slip event (red).

Slow slip event

- Located at the downdip limit (Fig. 8)
- Takes half a year to a year
- Ref. event: $V_{max} = 4.5 * 10^{-6}$ m/s
  $t_{min} = 2.1 * 10^{3}$ sec. $T_{total} = 186$ days

Concluding remarks

- Closed the gap between long-term geodynamic models and seismic models.
- Slip behaviour ranges from stable sliding to aperiodic seismic slip.
- We can track the surface displacement and mantle movement during the seismic cycle.
- Lower boundary condition needs fixing for accurate locking and displacement tracking

References: [1] Gerya and Yuan, Robust characteristics method for modelling multiphase visco-elasto-plastic thermo-mechanical problems, PEPI, 2007 [2] van Dinther et al., The seismic cycle at subduction thrusts: Insights from seismo-thermo-mechanical models, JGR, 2013b [3] Herrendörfer et al., An invariant rate- and state-dependent friction formulation for viscoelastoplastic earthquake cycle simulations, JGR, 2018 [4] van Zelfst et al., Modelling Megathurst Earthquakes Across scale: One-way coupling from Geodynamics and Seismic Cycles to Dynamic Rupture, AGU, 2019 [5] Liu and Rice, Spontaneous and triggered aseismic deformation transients in a subduction fault model, JGR, 2007