Simulating earthquake cycles using laboratory-derived, physics-based friction with multiple deformation and healing mechanisms

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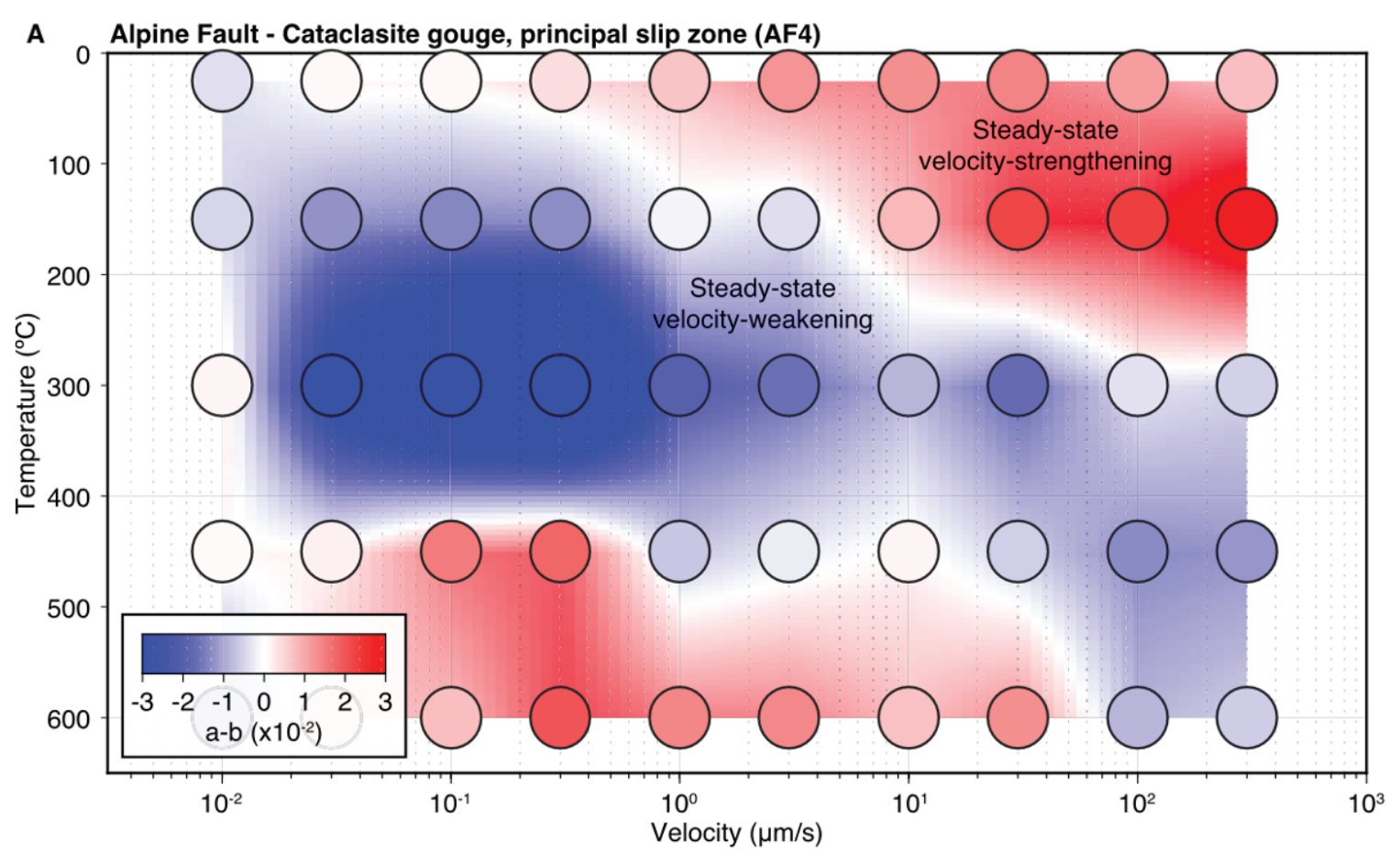
Motivation

Earthquake cycles are governed by dynamically evolving friction on geologic faults. Laboratory experiments reveal a three-regime frictional behavior for various rocks. The classic rate- and state-dependent friction law fails to capture the full range of observed behaviors. Moreover, the empirical nature hinders extrapolation of lab results to large-scale natural faults. To address these limitations, we propose a new simulator based on a physical friction model to extrapolate the inferred rheology from laboratory experiments and to understand earthquake dynamics.



Mechanical data: Niemeijer et al. (2016), Figure: Barbot (2023)

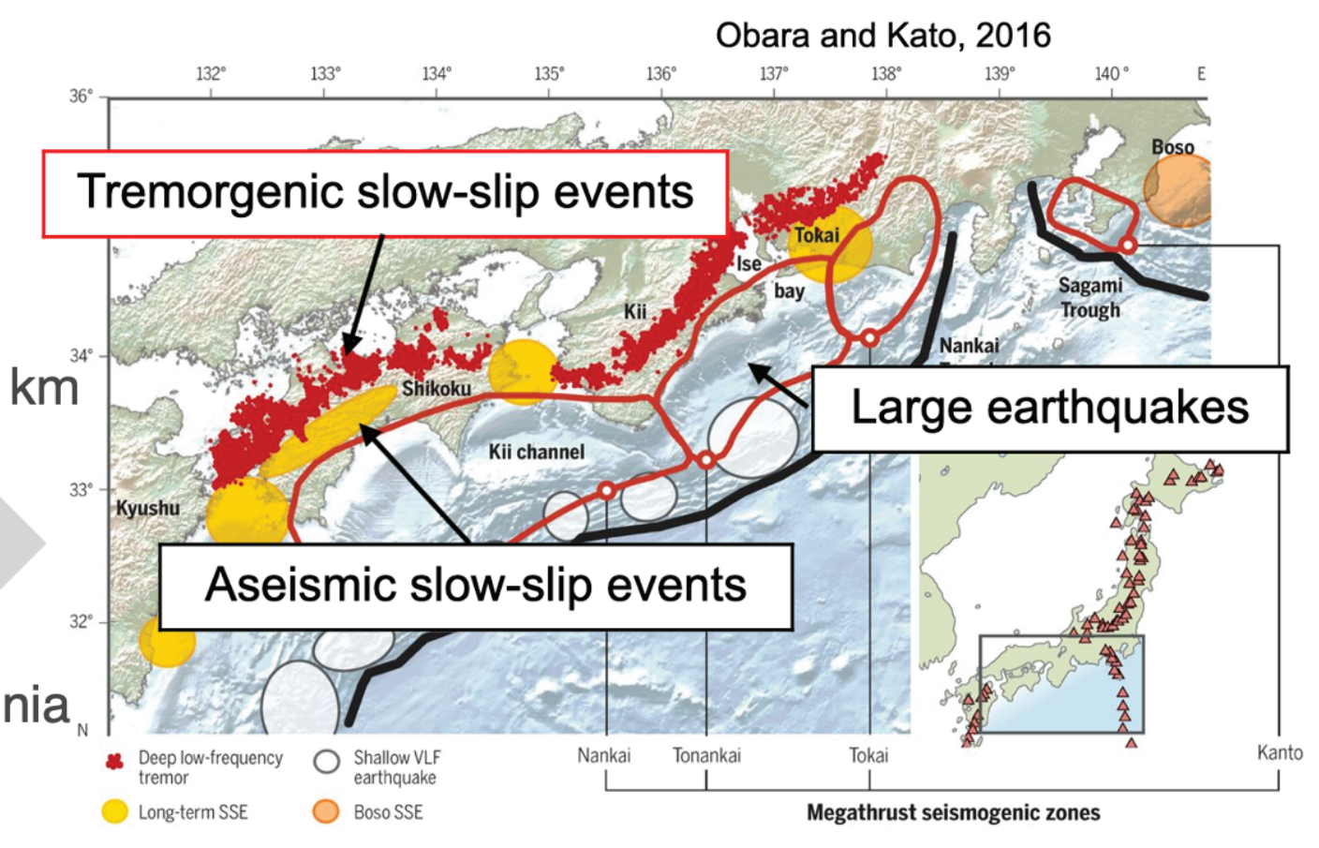
μm-mm-cm-m

m-100s km-1000s km

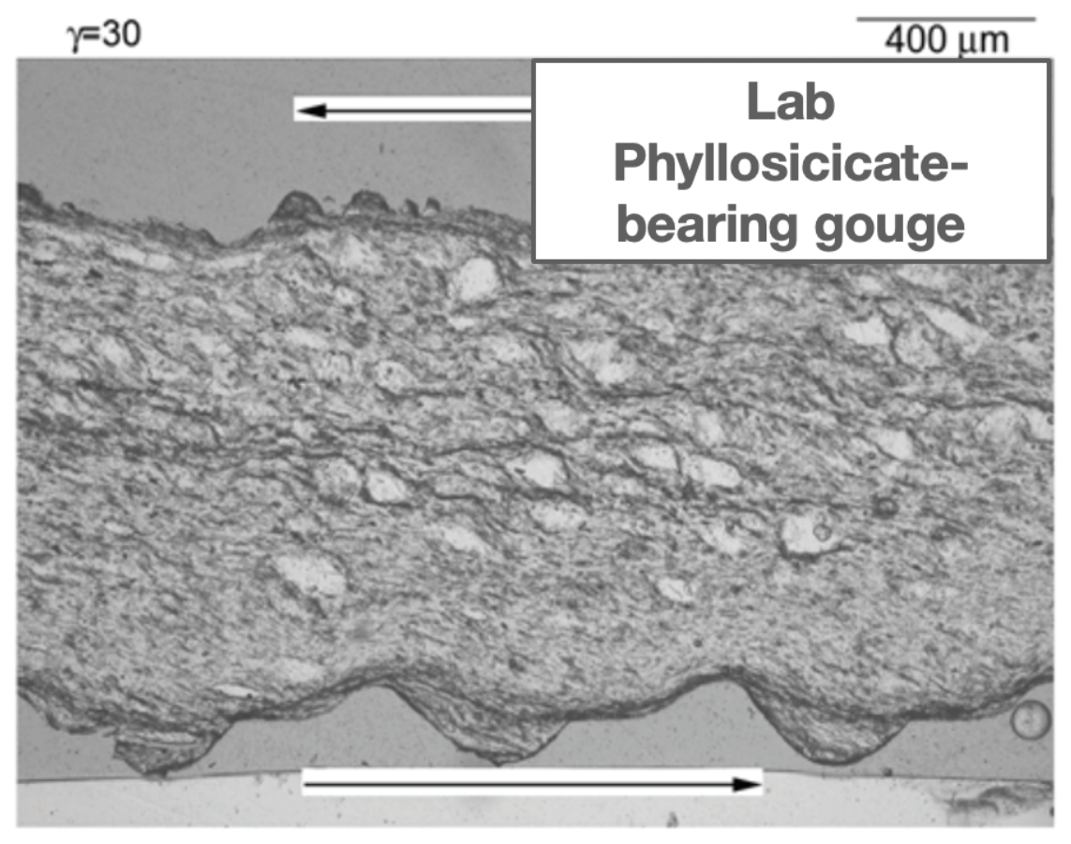
Explain and forecast earthquakes?

seconds-hours-days

seconds-years-millennia



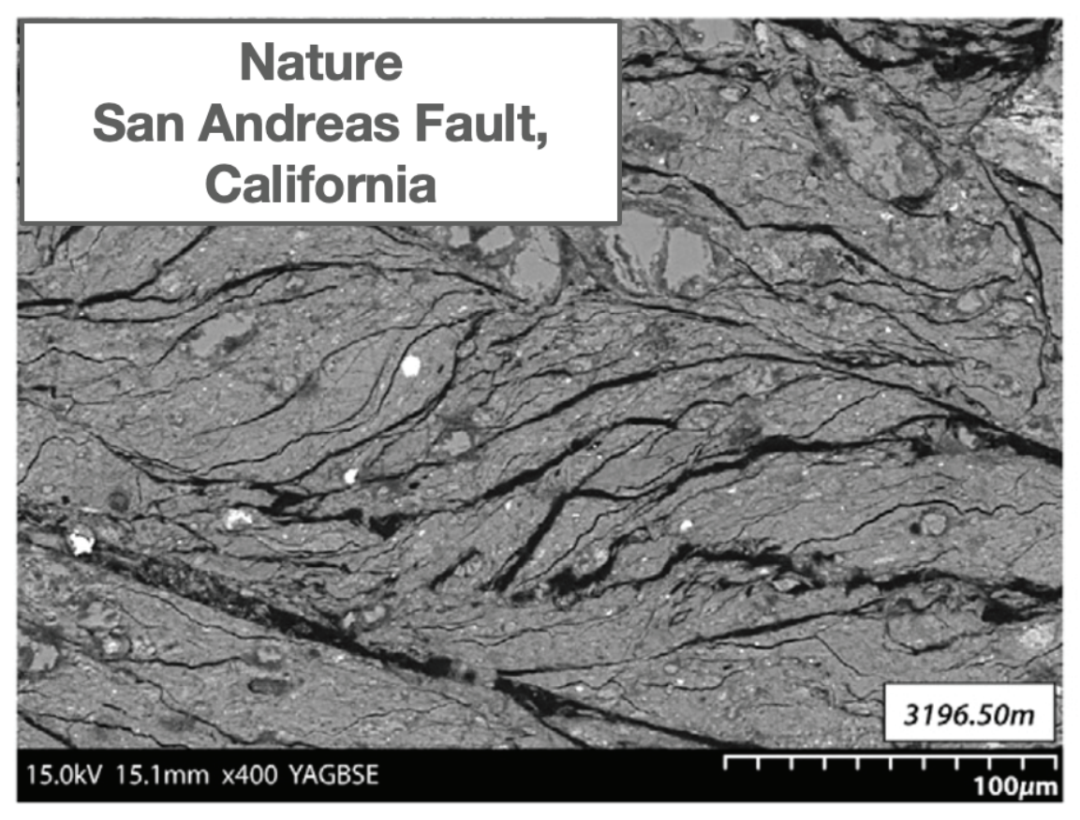
Diverse fault slip behaviors observed in nature



Microstructure in lab (Niemeijer and Spiers, 2007)

Same microscale mechanisms

Cataclasis
Subcritical crack growth
Pressure solution
Crack sealing



Microstructure in nature (Holdsworth et al., 2011)

Constitutive law

The constitutive behavior of rocks measured in lab experiments in quasi-static, isobaric condition is captured a constitutive law that include competitions of multiple deformation and healing mechanisms (Barbot, 2022, 2023)

$$V/V_0 = \left(\frac{\tau}{\mu_0\bar{\sigma}}\right)^{n_1}\left(\frac{d}{d_0}\right)^{-m_1}\exp\left[-\frac{Q_1}{R}\left(\frac{1}{T}-\frac{1}{T_{w1}}\right)\right] + \left(\frac{\tau}{\mu_0\bar{\sigma}}\right)^{n_2}\left(\frac{d}{d_0}\right)^{-m_2}\exp\left[-\frac{Q_2}{R}\left(\frac{1}{T}-\frac{1}{T_{w2}}\right)\right]$$

The contact area, which controls frictional strength, evolves as a result of healing and rejuvenation,

$$\frac{\dot{d}}{d} = \frac{G_1}{p_1 d^{p_1}}\exp\left[-\frac{H_1}{R}\left(\frac{1}{T}-\frac{1}{T_{h1}}\right)\right] + \frac{G_2}{p_2 d^{p_2}}\exp\left[-\frac{H_2}{R}\left(\frac{1}{T}-\frac{1}{T_{h2}}\right)\right] - \frac{\lambda V}{2h}.$$

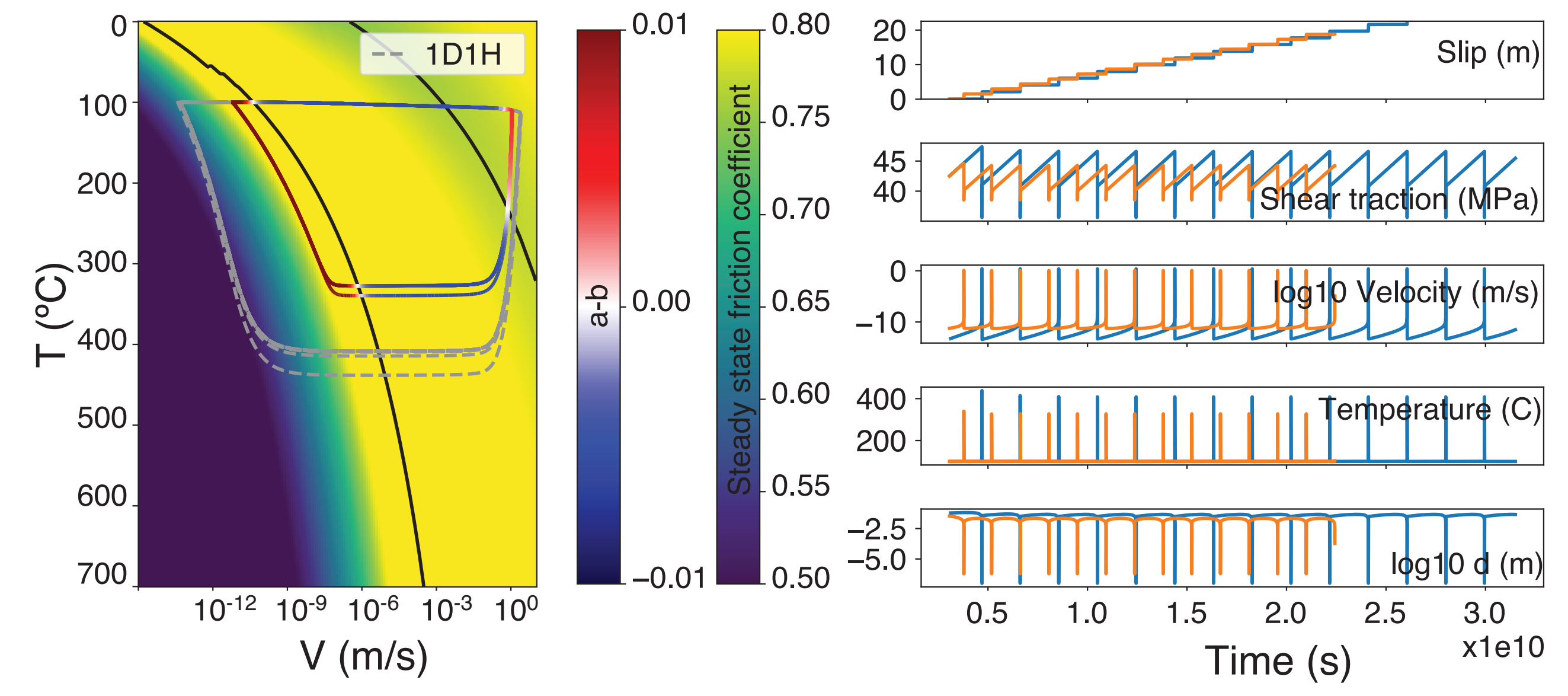
On-fault temperature evolves over earthquake cycles as a result of shear heating and heat diffusion,

$$\dot{T} = -\frac{D}{W^2}(T-T_b) + \frac{\tau V}{\rho c w}$$

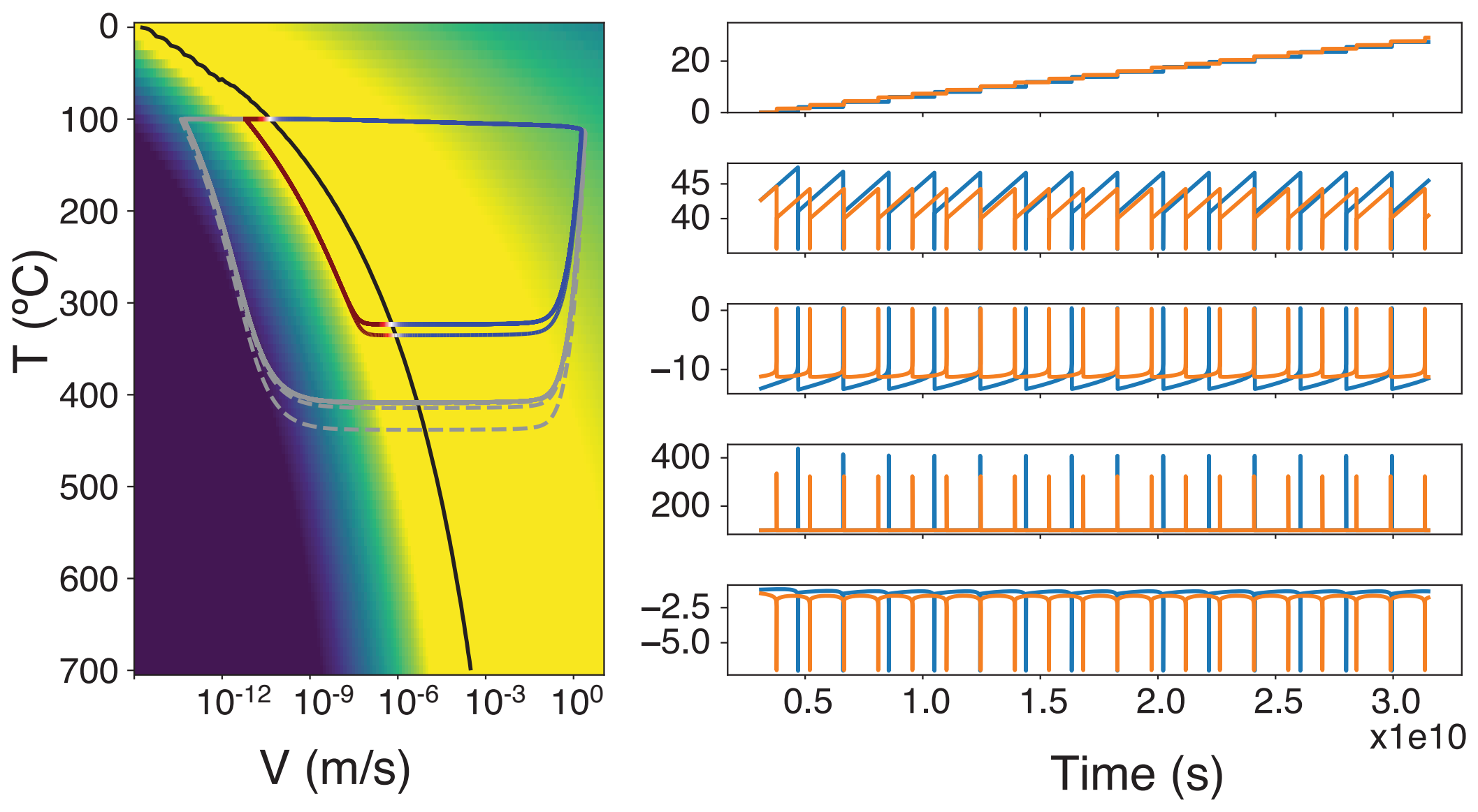
Spring-slider simulations with Westerly Granite

- Competing **deformation** mechanisms increase the locking velocity while decreasing peak stress/strength, slip, and temperature rise.
- The incorporation of a **healing** mechanism results in a reduced dynamic stress drop.

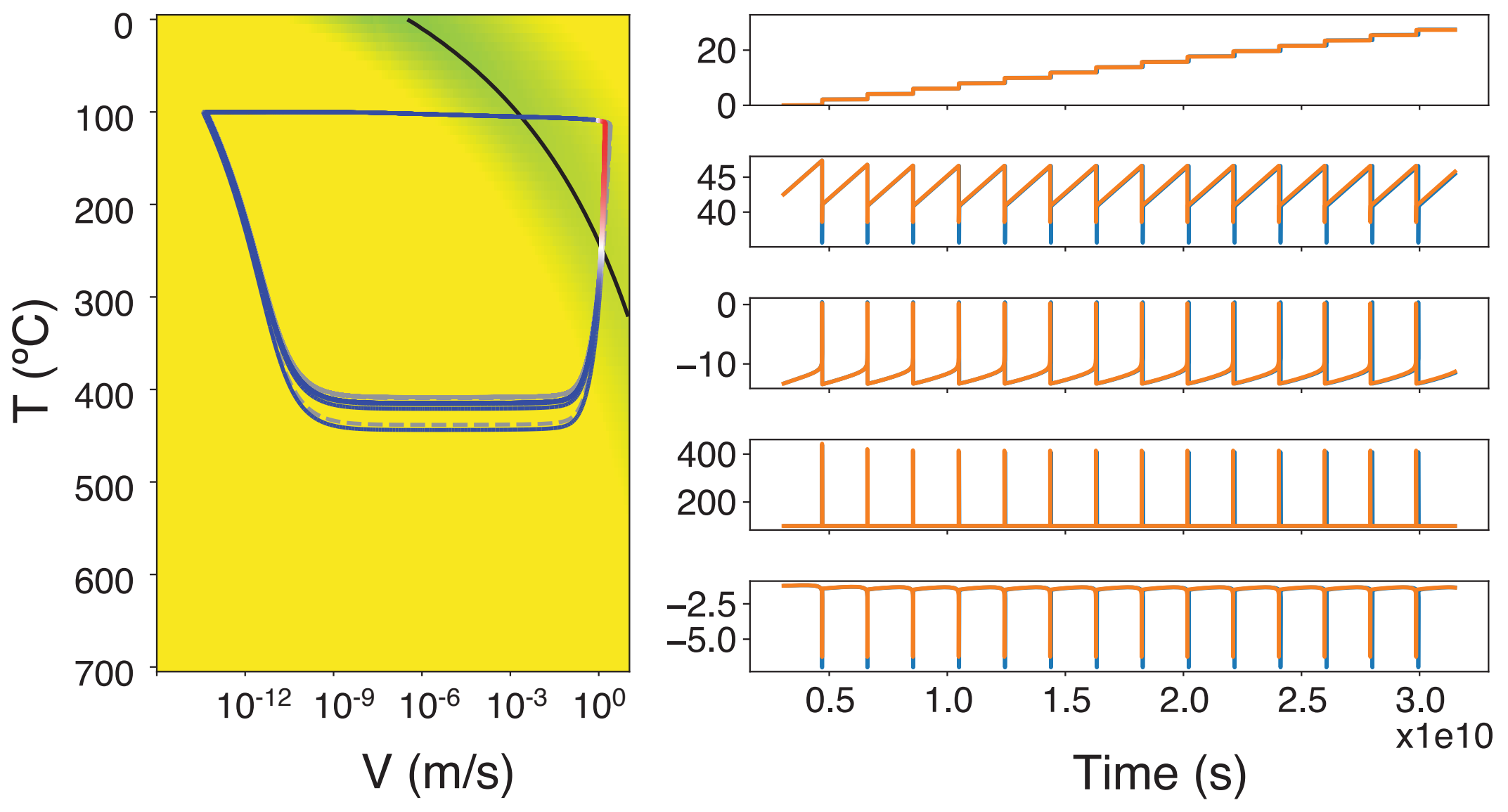
2 Deformation + 2 Healing Mechanisms



2 Deformation + 1 Healing Mechanisms

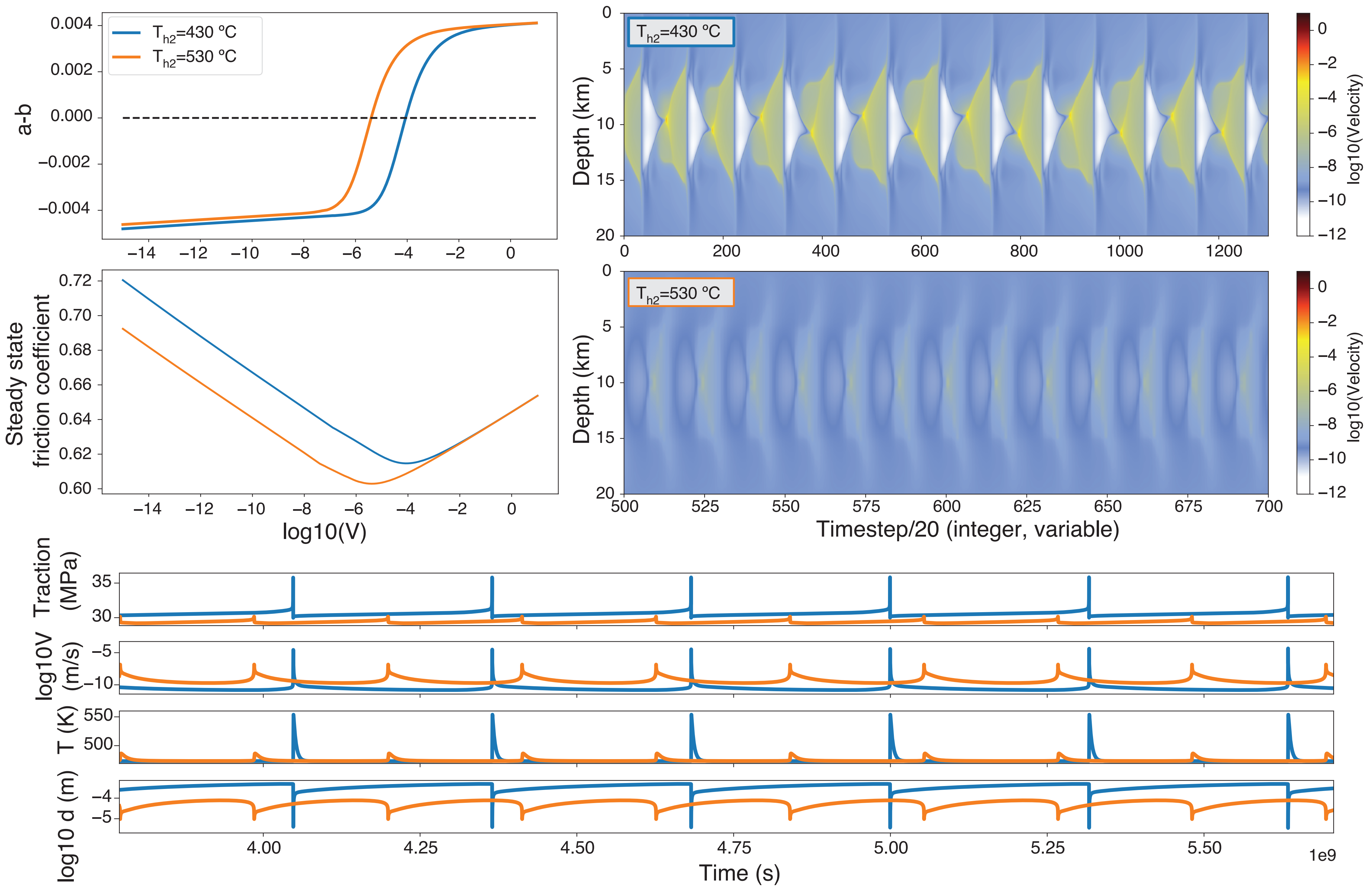


1 Deformation + 2 Healing Mechanisms



Slow-slip events due to switching of healing mechanisms

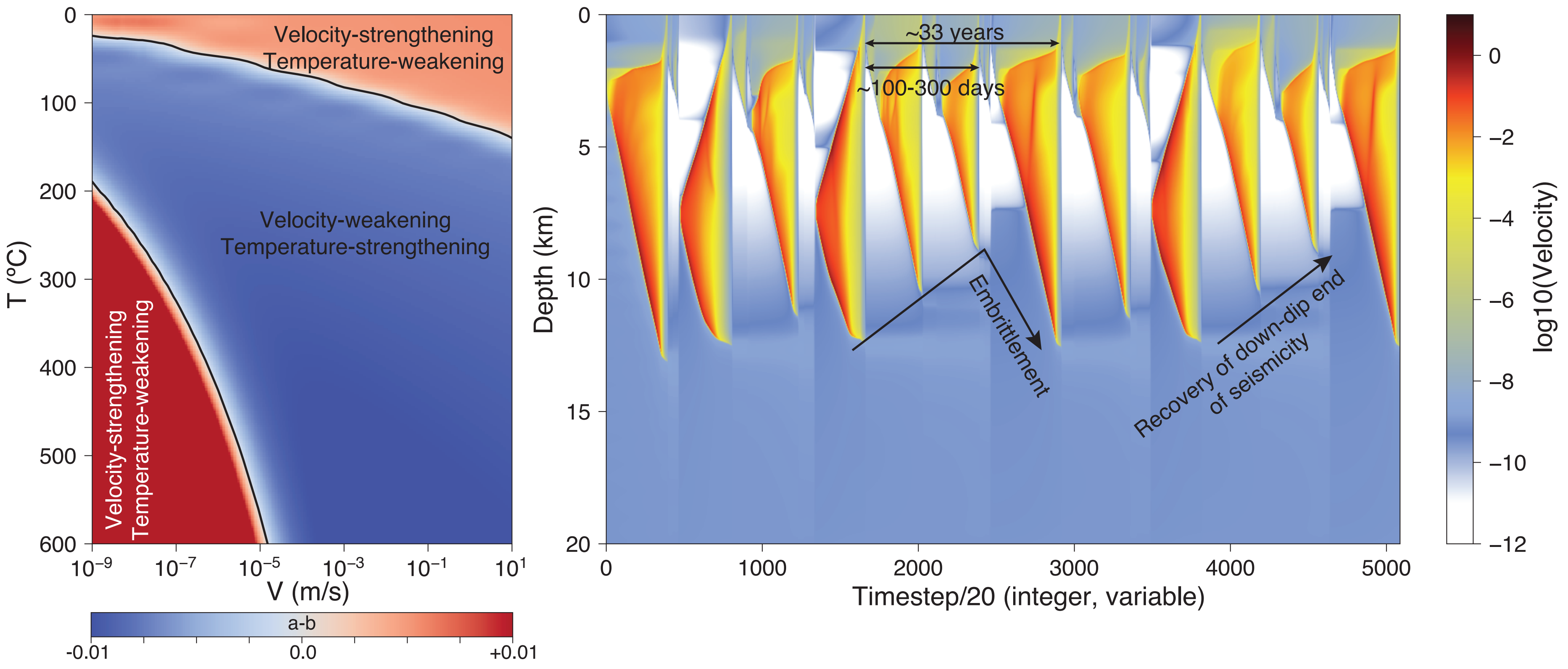
Transition of healing mechanisms results in a transition from velocity-weakening to velocity-strengthening with increasing velocity at low temperature (0-200 °C). This velocity-dependence, controlled by the activation energy (H_2) and temperature (T_{h2}) of the healing mechanism, may explain shallow slow-slip events, as observed in Hikurangi (85-230 °C), Nankai (85-210 °C), and Costa Rica (12-60 °C) (Saffer & Wallace, 2015). This is similar to previous implementation of cut-off velocity (Shibazaki & Iio, 2003) and velocity-dependent frictional parameters (Im et al., 2020), but this model shows a delayed transition due to finite slip required for state evolution. Previous models omit the temperature dependence of friction. However, the cut-off velocity increases with temperature, likely implying depth-dependent characteristics of slow-slip events, or even making this mechanism difficult to explain deep slow-slip events.



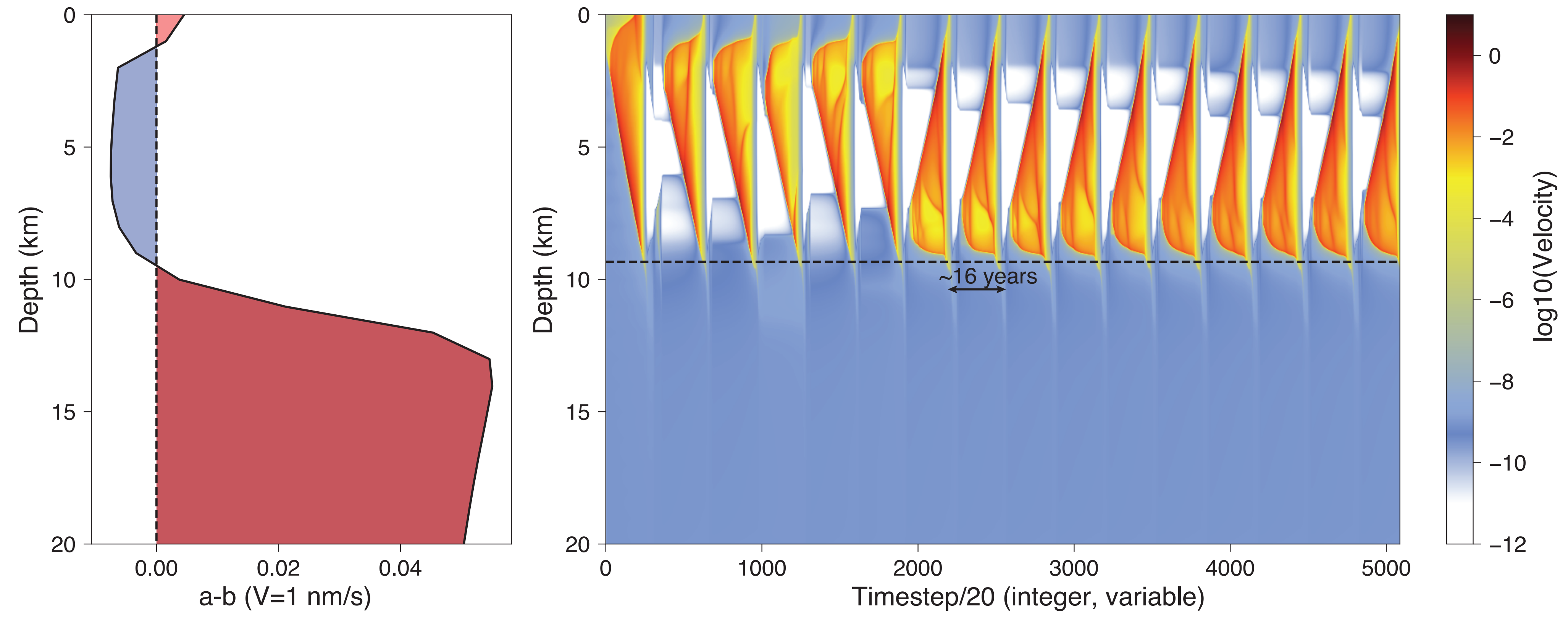
Deep-penetrating ruptures due to switching of deformation mechanisms

Velocity increases triggered by seismic events can embrittle the nominally creeping section down-dip of the seismogenic zone. This embrittlement facilitates ruptures to propagate beyond the nominal seismogenic limit. Subsequently, the down-dip limit of seismicity rapidly migrates up-dip following the mainshock. Enhanced dynamic weakening at fast slip rates (e.g. thermal pressurization) may also contribute to deep-penetrating ruptures (Jiang and Lapusta, 2016).

Competing deformation and healing mechanisms --> Dynamically evolving a-b, bH-aQ



Single deformation and healing mechanism --> Nearly constant a-b, bH-aQ



References

Barbot (2022 JGR), Barbot (2023 AGU Advances), Blanpied et al. (1995 JGR), Chester (1994 JGR), Holdsworth et al. (2011 JSG), Im et al. (2020, Nat. Geo.), Jiang & Lapusta (2016 Science), Niemeijer et al. (2016 JGR), Niemeijer & Spiers (2007 JGR), Obara & Kato (2016 Science), Saffer & Wallace (2015 Nat. Geo.), Shibazaki &Iio (2003 GRL).