Simulations of Seismic and Aseismic Slip on a Heterogeneous Fault with Temperature-dependent Creep

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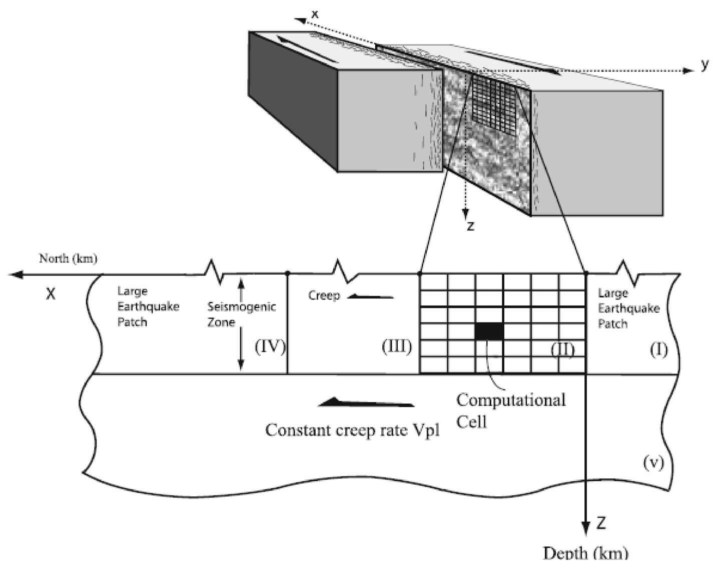
Abstract



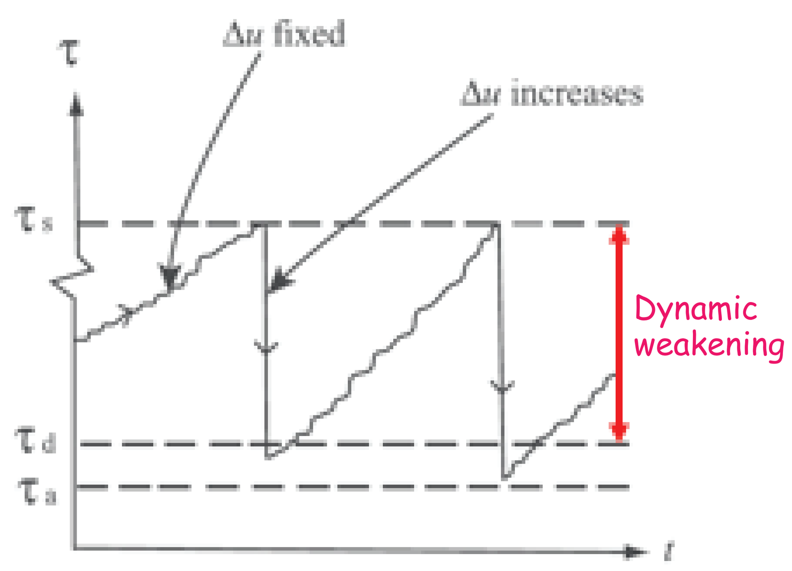
We study the evolution of seismicity and seismic/aseismic slip partitioning on a fault using a generalized version of the Ben-Zion and Rice (1993) model for a discrete cellular fault in elastic halfspace. Previous versions of the model were shown to produce a wide variety of realistic results (e.g., frequency-size statistics, hypocenter distributions, slip distributions and temporal occurrence) using distributions of static and kinetic friction levels and creep properties that vary in space but are fixed in time. In the present study we incorporate heat generation due to slip within a 10 cm wide zone, subsequent diffusion into the surrounding halfspace, and related changes of temperature and temperature-dependent creep on the fault. We assume a power law dependency of creep on the local shear stress, with temperature-dependent parameters based on the Arrhenius equation. Temperature rises due to slip episodes lead to increased aseismic slip, which can lead to further stress concentration in a feedback loop. The partitioning of seismic/aseismic slip and the temporal distribution of seismicity are strongly affected by the activation energy in the Arrhenius equation, and frictional parameters that control the local stress drop after failure. Our initial investigations attempt to clarify changes of the fault behavior associated with variations of these two parameters.

Strength change parameter

Brittle failure occurs when the local stress at a cell reach the static strength level. The strength drops to dynamic level τ_d, and the difference τ-τ_a gives a transient stress drop during one composite brittle failure episode, where τ is stress before failure.

$$\varepsilon_D = (\tau_s - \tau_a)/(\tau_s - \tau_d)$$

τ_s: static brittle failure strength
τ_d: dynamic brittle failure strength
τ_a: stress remaining on a cell during a composite brittle event

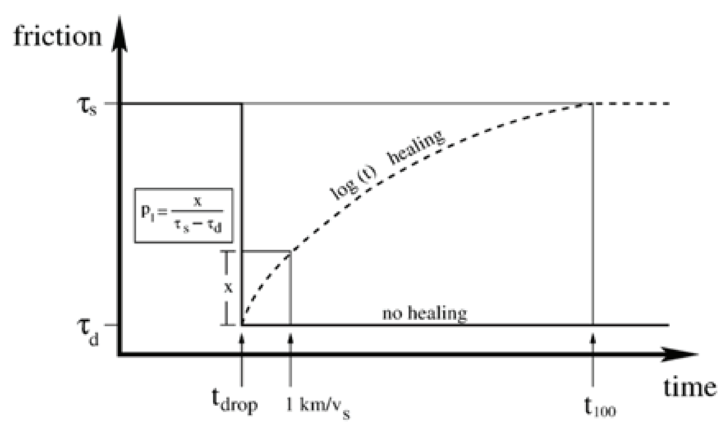


Frictional strength healing

To apply a more realistic friction law, we introduce a time-dependent healing of the form

$$\tau_d(t) = \tau_{d0} + C\ln\left(1 + \frac{t}{t_{Heal}}\right)$$

where τ_{d0} is the initial dynamic strength, and tHeal gives the time interval required for complete healing to static level.



(Zöller et al., 2004)

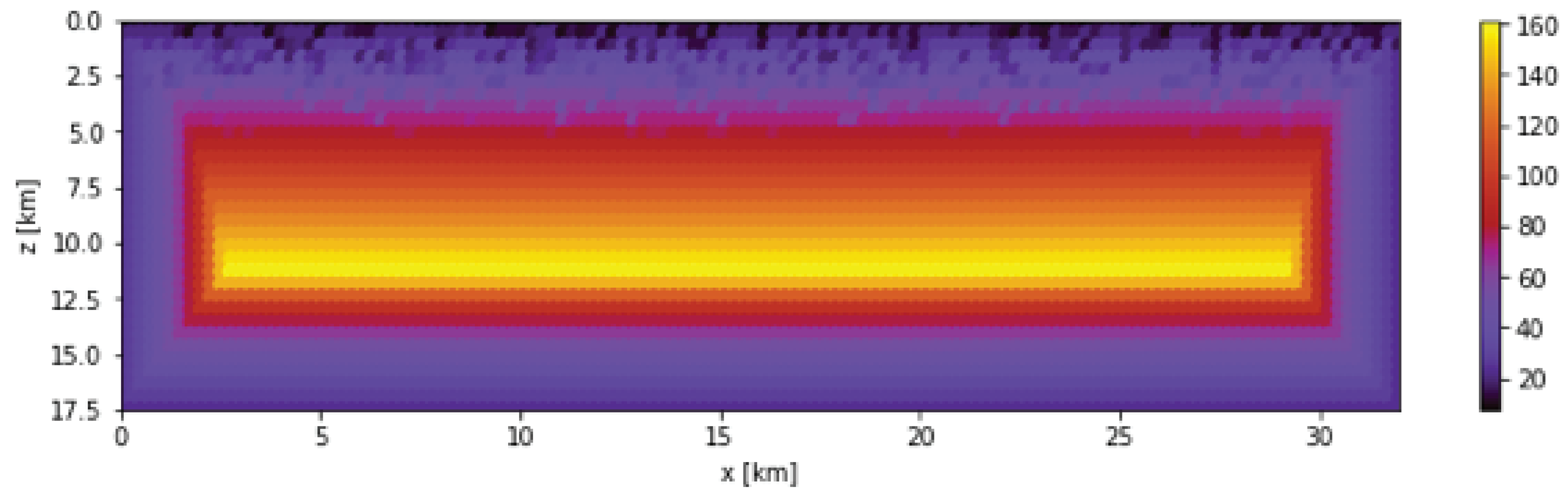
Strength profile

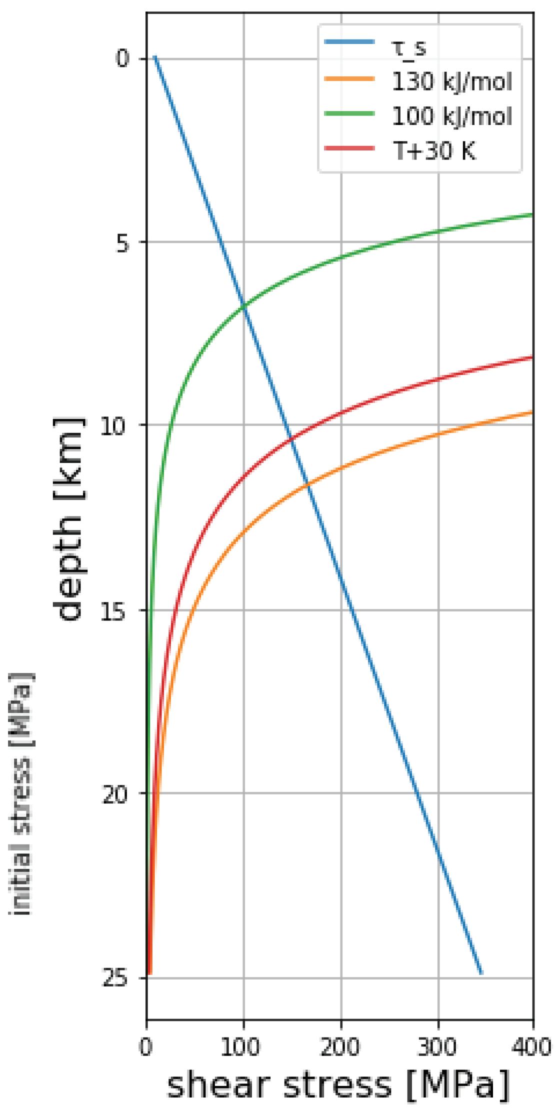
The failure envelope of the model is illustrated by the collection of minima between the static brittle strength τ_s, and τ_c, the stress required for a creep-slip at plate velocity.

$$\tau_s(x,z) = \tau_0 + (\rho - \rho_w)gz$$

$$\tau_c(x,z) = \left[\frac{v_p / w}{A\exp\left(-\frac{E(x,z)}{RT(z)}\right)}\right]^{\frac{1}{3}}$$

τ_0: cohesion
ρ, ρ_w: rock and water density respectively
v_p: plate velocity
w: fault loading width
A: Arhenius amplitude
E: fault activation energy
T: temperature, linear with depth



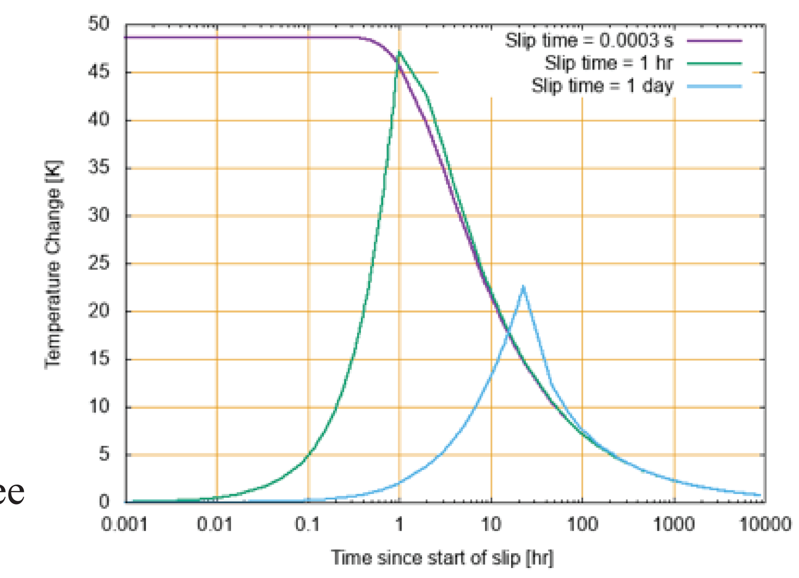


Thermal mechanism and rock healing

We assume a temperature dependent creep based on Arrhenus equation below.

$$v_c(x,z) = wA\tau(x,z)^3\exp\left(-\frac{E(x,z)}{RT(z)}\right)$$

Post-seismic temperature increase will raise the creep velocity, which leads to furthur stress concentraion around fracture area. We apply a cooling function from Cardwell et al., 1978, assuming constant heat rate during each step and 1D diffusion from fault surface into the half-space. On the right we are showing temperature changes from three events with same slip = 1m and different durations.



$$T = T_0 + \frac{\sigma_f D}{2\rho c_p w\tau}\int_0^{\tau}\left\{erf\left[\frac{x+\frac{w}{2}}{(4\kappa[t-t_0])^{\frac{1}{2}}}\right] - erf\left[\frac{x-\frac{w}{2}}{(4\kappa[t-t_0])^{\frac{1}{2}}}\right]\right\}dt_0, t > \tau$$

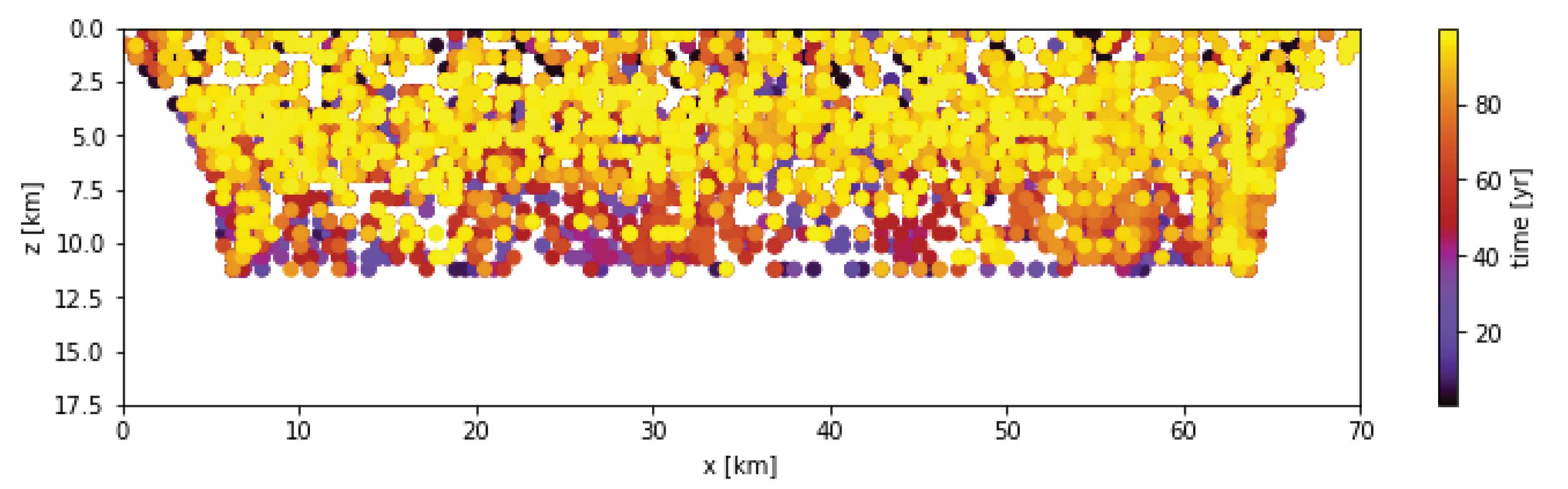
σ_f: stress on the fault
D: slip on the fault
τ: duration of one event
κ: diffusivity of the half-sapce
w: width of the slip zone

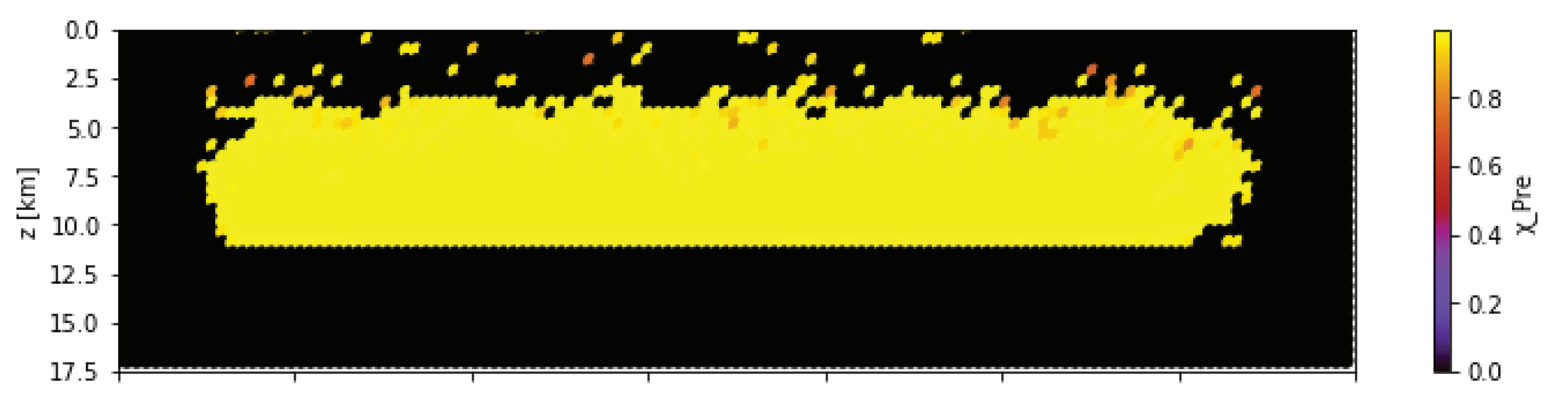
A drop in the activation is applied after a brittle slip to approximate rock damage. Combining a rock healing faunction from Snieder et al., 2017, we are able to show that fracture zone lose its ability to accumulate stress concentration until its activation is recovered to a certain level. Two individual cells are chosen to demonstrate the process, as shown below.

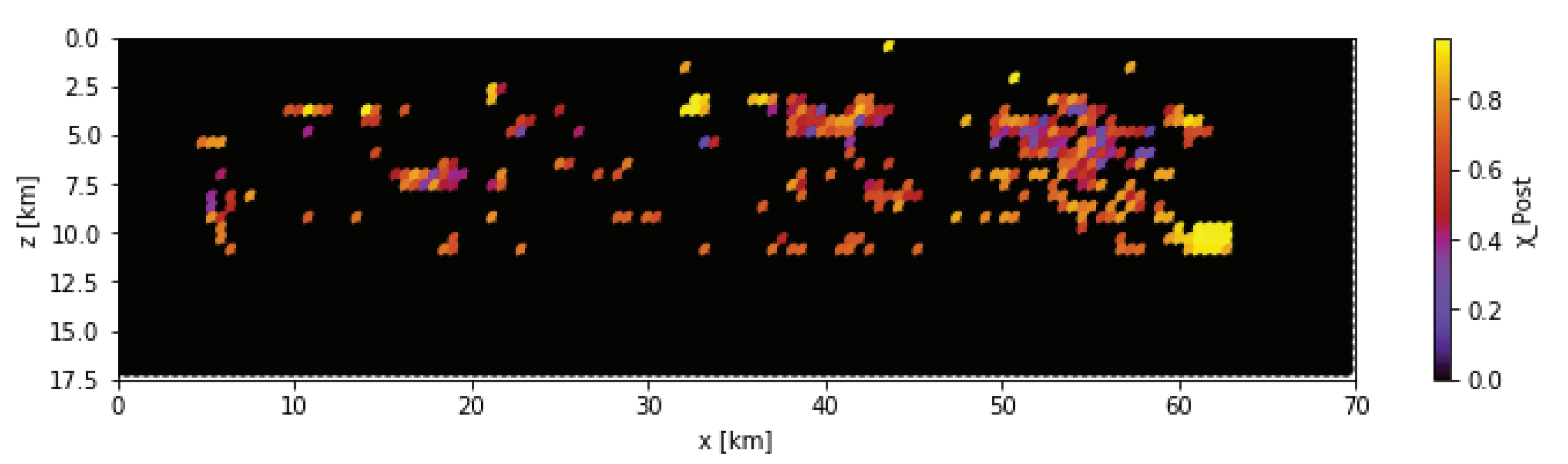
$$E(t) = E_0\left[1 + \gamma\int_{\tau_{min}}^{\tau_{max}}\frac{1}{\tau}e^{-\frac{t}{\tau}}d\tau\right]$$

γ: scaling factor
τ_{min}: minimum relaxation time
τ_{max}: maximum relaxation time

Results







Top left panel: model hypocenters for the case of uniform brittle properties. Color bar indicates the time of each event. The number of earthquakes generated during a 100-year simulation is over 14000.

Middle left panels: coupling coefficient on the fault one month before and after a Magnitude = 6.2 event.

$$\chi = \frac{\Delta\varepsilon_{seismic}}{\Delta\varepsilon_{seismic} + \Delta\varepsilon_{aseismic}}$$

Couping coefficient drops significantly after a large events due to the post-seismic temperature increase and rock damage.

Bottom left and middle: Moment magnitude vs. time and cumulative frequency-size statistics are plotted. Larger events tend to trigger more aftershocks.

Bottom right: Case with slower strength healing. More aftershocks are generated. However, no aftershock decay is observed.

Right panel: two individual cells are selected to demostrate two types of fault behavior. Top one is a brittle cell and bottom is a conditionally stable creeping cell.