3D earthquake sequence simulations accounting for thermal pressurization of pore fluids

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Hydrothermal effects on the frictional resistance

In the deformation of granular material like fault gouge, it is known that high pore pressure decreases the frictional resistance by reducing the solid-solid contact normal stress.

Effective stress law

Total normal stress (positive in compression)

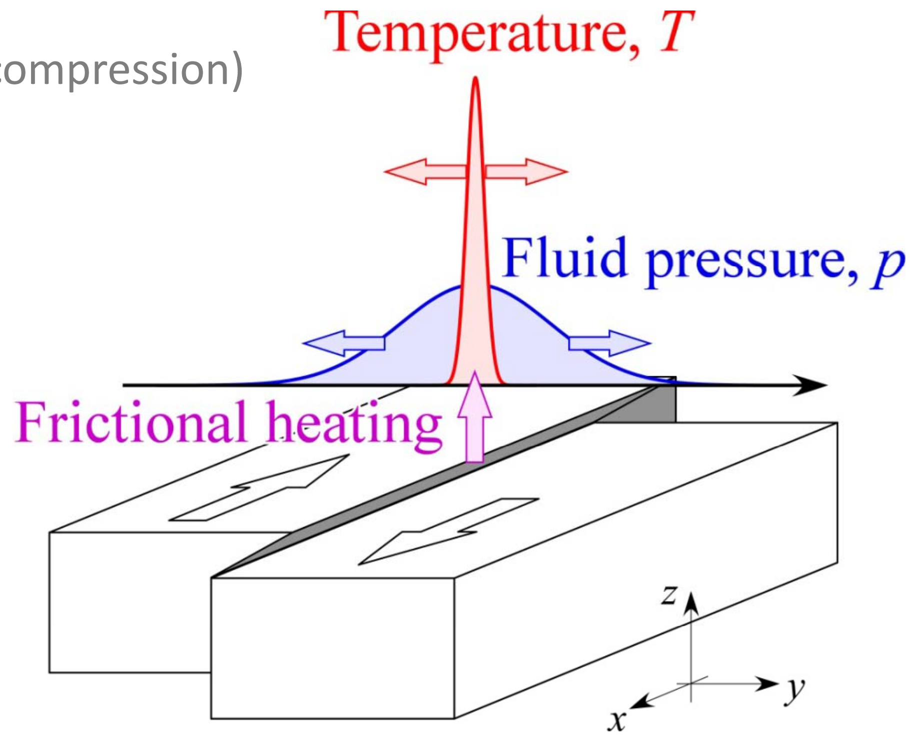
Pore pressure

$$\tau = f\sigma_e = f\left(\sigma_n - p\right)$$

Effective normal stress

Shear traction

Friction coefficient



"Thermal pressurization"

Since the thermal expansivity of water is much larger than that of rocks, frictional heating can increase p if the surrounding medium is not very permeable.

This mechanism was first introduced in considering catastrophic landslides [Hibab, 1967]. Sibson [1973] explained the scarcity of pseudotachylytes by this mechanism, with a lot of later studies.

1999 (M_w 7.6) Chi-Chi, Taiwan, earthquake

It has been pointed out [e.g. Ma et al., 2003] that the long-period component is dominant in the northern region where the fault slip is larger than the southern region.

Temperature measurements at bore holes in the North [Tanaka et al., 2006; Kano et al., 2006] showed that the frictional resistance is only $\sim 0.1 \times \sigma_n$ during the earthquake.

Andrews [2005] showed that the long-period component in the strong motion data increases when thermal pressurization is introduced locally in the North in a dynamic rupture propagation calculation.

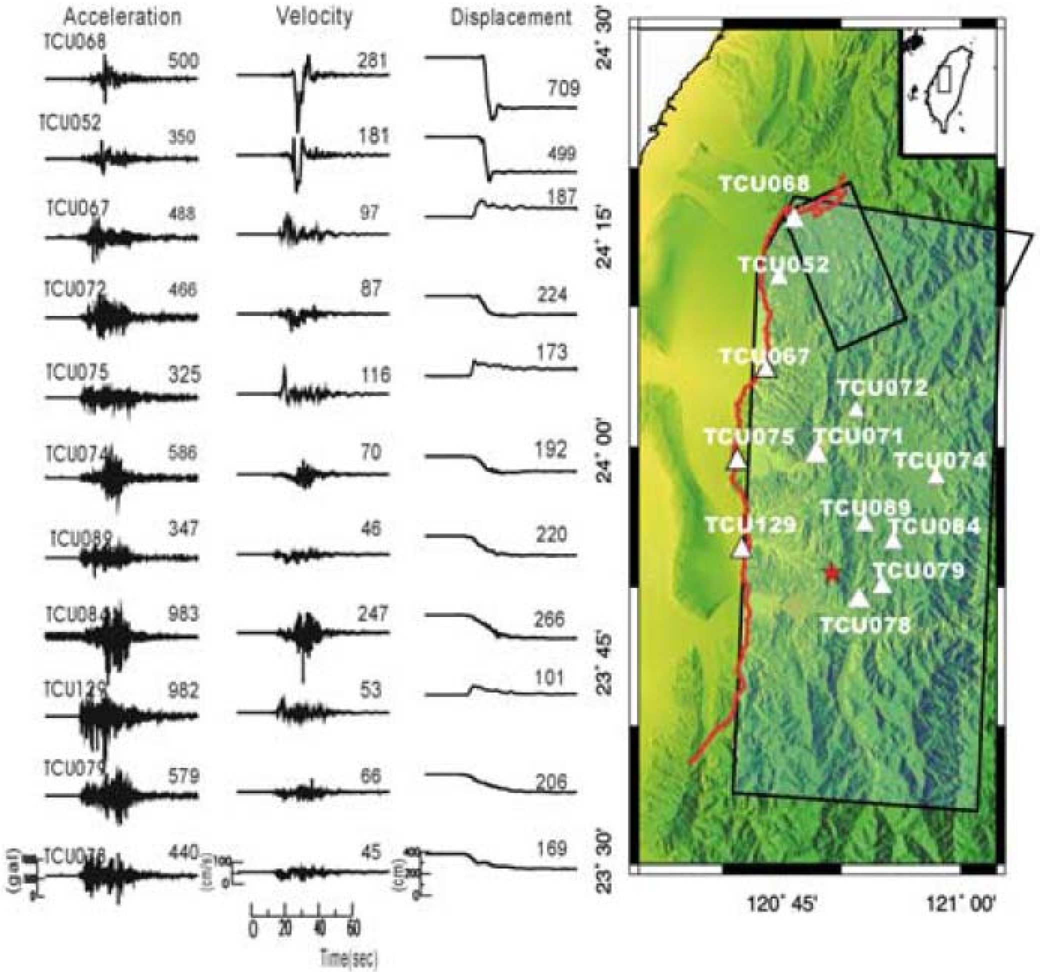
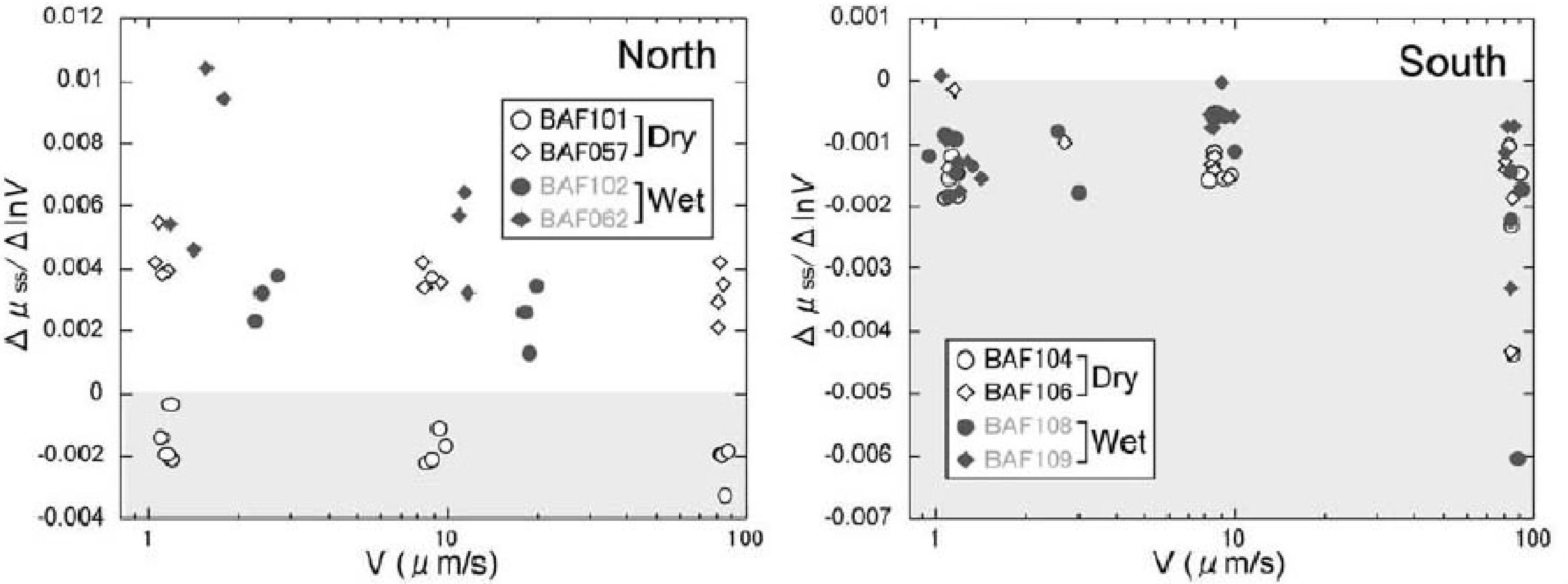


Figure from Ma et al. [2003]

Lab-measured physical properties rate- and state- parameters

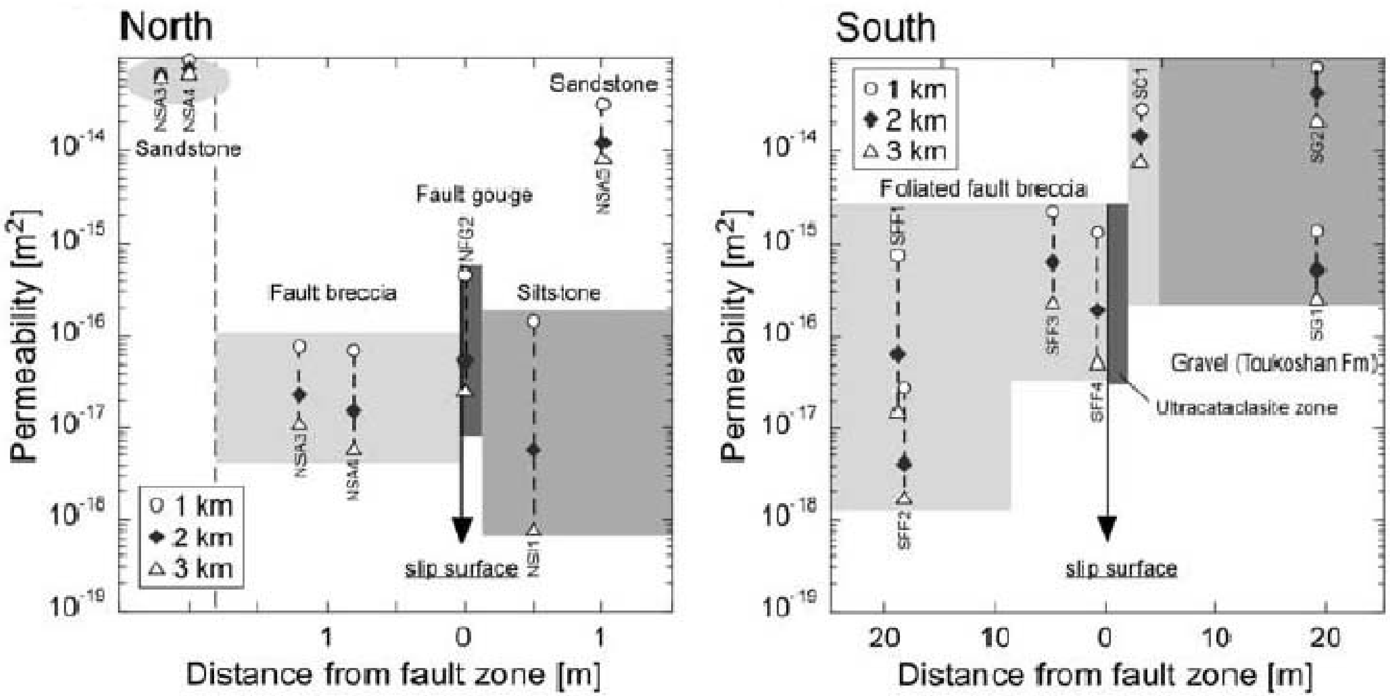


Samples are collected from bore holes in the northern and southern regions from a fault zone which ruptured 1999 at 200 – 300 m depth.

North: Rate-hardening
South: Rate-weakening

Tanikawa and Shimamoto, 2009

Lab-measured physical properties
permeability



North: Less permeable
South: More permeable

Tanikawa and Shimamoto, 2009

Summary of measured physical properties

[Tanikawa and Shimamoto, 2009]

South :

Rate-weakening

Susceptible to nucleation

More permeable

North :

Rate-hardening

Less permeable

Susceptible to thermal pressurization

This data serves as motivation for exploring heterogeneities in rate dependence and permeability (hydraulic diffusivity) along the faults.

We caution that the data is based on only two points at shallow depths ($\sim$ 200-300 m).

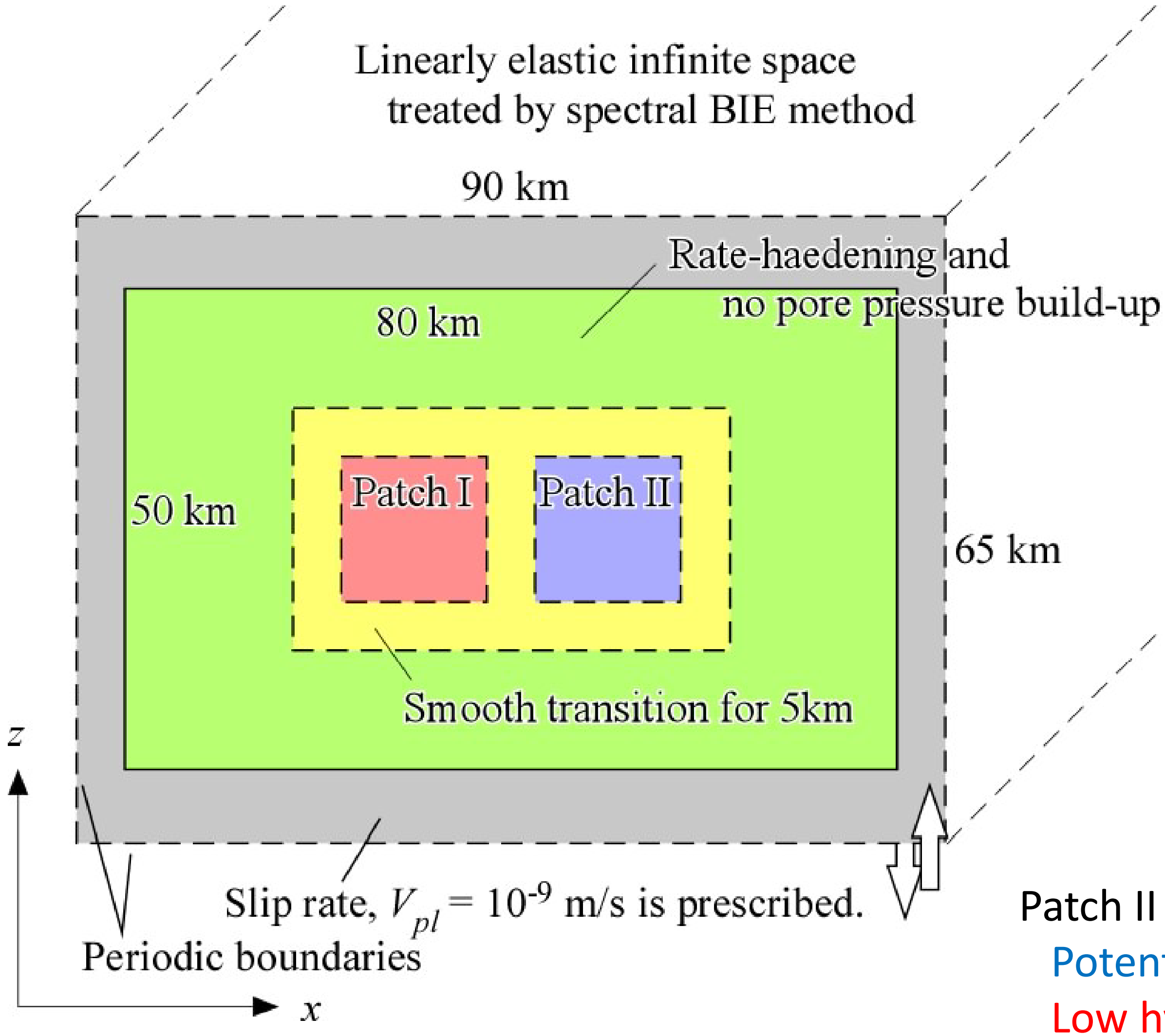
Aim of this work

- To develop a methodology for long-term, earthquake sequence simulations fully accounting for the inertial and hydrothermal effects.

- To see how the heterogeneities in the frictional and hydraulic properties (as observed experimentally) affect earthquake cycles: spatio-temporal slip distribution and characteristics of each dynamic event.

- Especially, to see if it is possible to produce differences in frequency content of seismic radiation from different parts of the fault, as observed in the 1999 Chi-Chi, Taiwan, earthquake.

Problem settings



Two patches (15 km x 15 km)

Patch I at negative x

Rate-weakening friction

High hydraulic diffusivity

Patch II at positive x

Potentially rate-hardening

Low hydraulic diffusivity

(susceptible to thermal pressurization)

Friction law on the fault (*y* = 0, *x* and *z* vary)

Effective stress law

$$\boldsymbol{\tau} = \frac{\mathbf{V}}{V} f \cdot (\sigma_n - p)$$

- f : Friction coefficient
- θ : State variable (slowness)
- σ_n : Total normal stress on the fault
- p : Fluid pressure
- V : $|\mathbf{V}|$

Rate- and state-dependent friction law

$$f = a \sinh^{-1}\left(\frac{V}{2V_0}\exp\left(\frac{f_0 + b\ln(\theta)}{a}\right)\right)$$

- a : Parameter representing direct effect
- b : Parameter representing evolution effect
- V_0 : Reference slip rate
- f_0 : Reference friction coefficient

State evolution law (aging law or slowness law)

$$\dot{\theta} = \frac{V}{L}\left(\theta_{ss}(V) - \theta\right) = \frac{V}{L}\left(\frac{V_0}{V} - \theta\right)$$

- L : Characteristic evolution length (slip)
- θ_{ss} : State variable at the stead state

Temperature and fluid pressure evolution

Diffusion of temperature normal to the fault

$$\frac{\partial T(x,y,z,t)}{\partial t} = -\alpha_{th}\frac{\partial^2 T}{\partial y^2} + \frac{\omega}{\rho c}$$

T : Temperature
α_{th} : Thermal diffusivity
ω : Heat generation per unit volume
ρ : Density
c : Heat capacity per unit mass

Diffusion of fluid pressure normal to the fault

$$\frac{\partial p(x,y,z,t)}{\partial t} = -\alpha_{hy}\frac{\partial^2 p}{\partial y^2} + \Lambda\frac{\partial T}{\partial t}$$

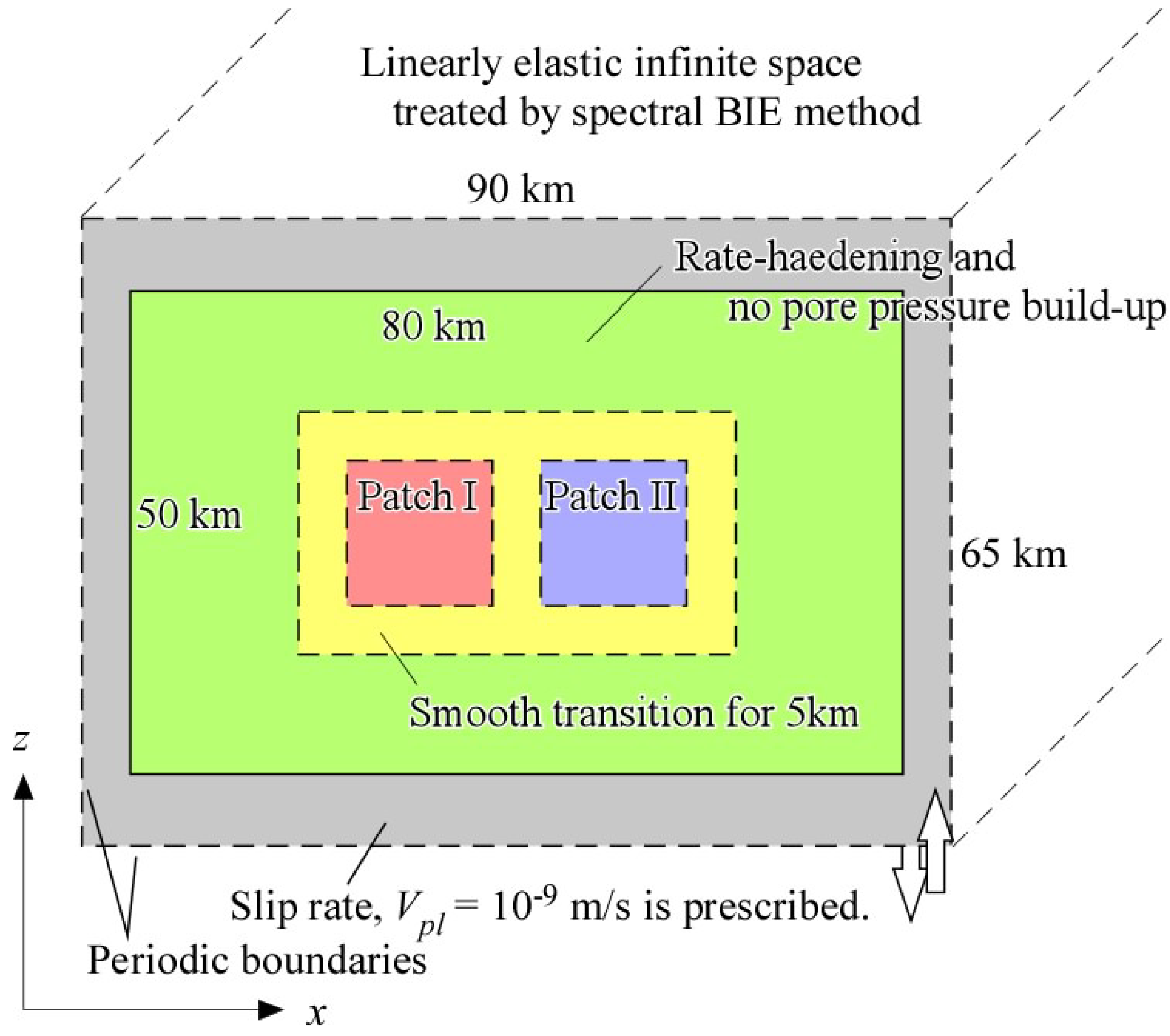
α_{hy} : Hydraulic diffusivity
Λ : Fluid pressure change / temperature change

Heat source distribution

$$\omega = \frac{\tau V}{w\sqrt{2\pi}}\exp\left(-\frac{y^2}{2w^2}\right)$$

w : Half width of the shear zone

We have developed a way to integrate these PDEs in time using a spectral method (Fourier basis) and semi-analytic time-advancing operator with iteration, which is unconditionally stable. Also, we do not need to store the history of heat generation. These features are highly suitable for simulating earthquake sequences.



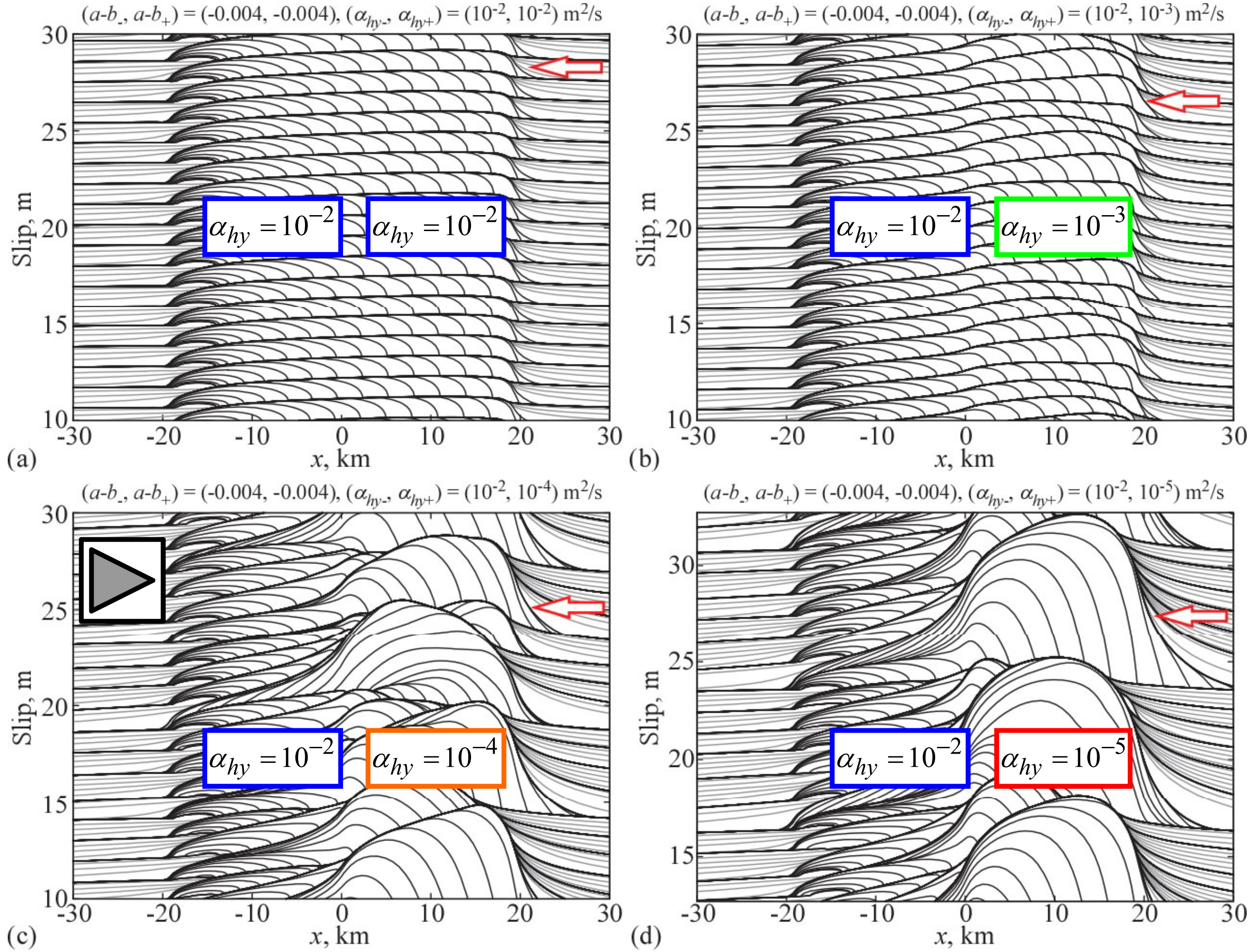
$\sigma_{e0} = 30$ MPa, $L = 4$ mm, $w = 1$ cm, $a = 0.01$

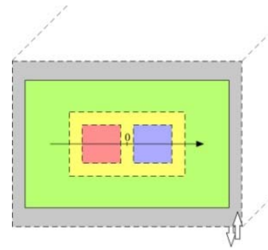
Patch I	$b = 0.014\ (a - b = -0.004)$	$\alpha_{hy} = 10^{-2}\ \mathrm{m^2/s}$
Patch II	$b = 0.006\text{-}0.014\ (a - b = 0.004\text{-}-0.004)$	$\alpha_{hy} = 10^{-2}\text{-}10^{-5}\ \mathrm{m^2/s}$

Heterogeneity in the hydraulic diffusivity

Slip distribution at $z = 0$, black lines every 1 sec during EQs and gray ones every 10 years

$a - b = -0.004$



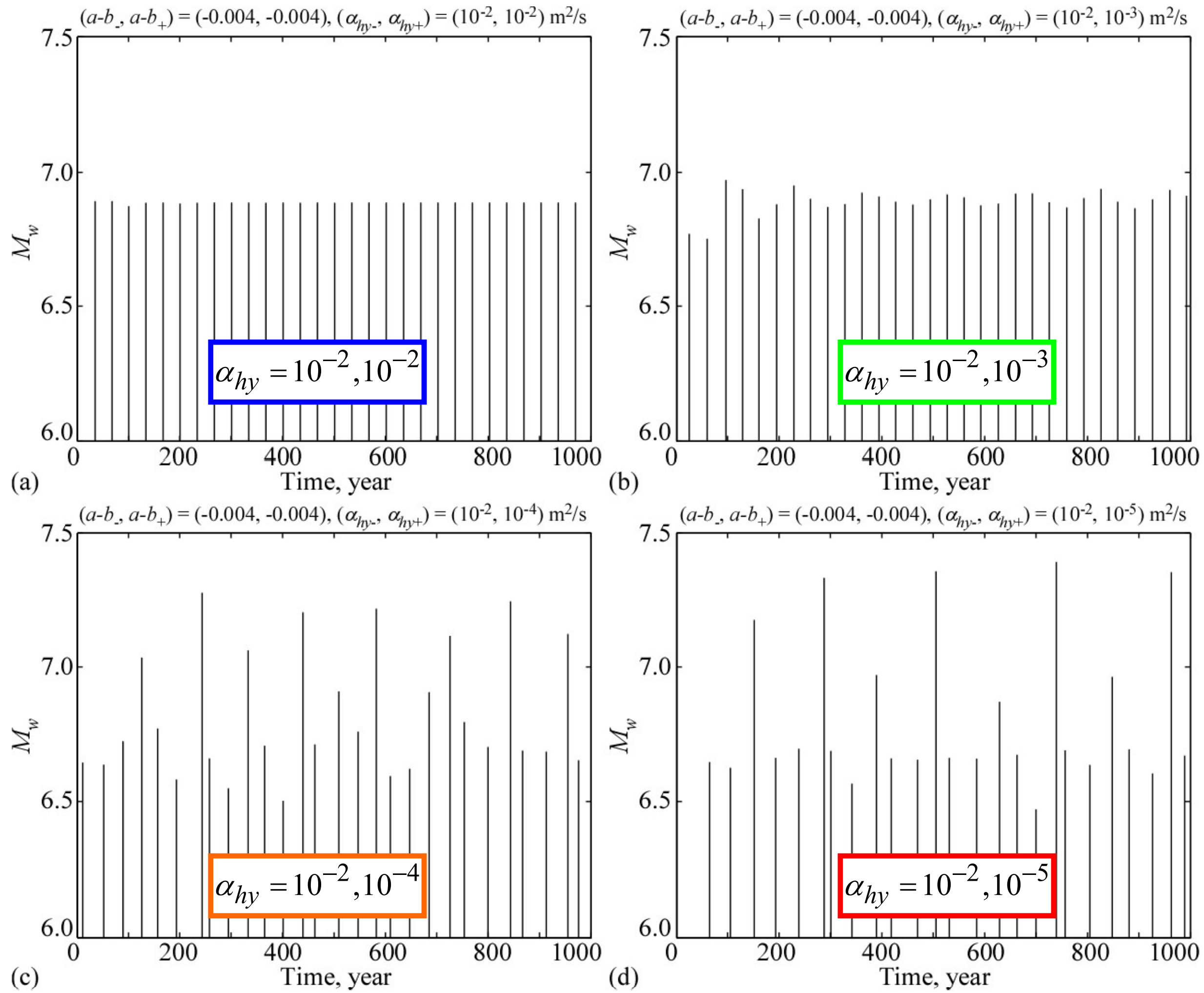


The region more susceptible to thermal pressurization has larger displacements in model-spanning events. The slip deficit in the other region is filled with smaller and more frequent events.

The resulting complexity in EQ magnitude distribution

Magnitude of the events as a function of time

$a - b = -0.004$



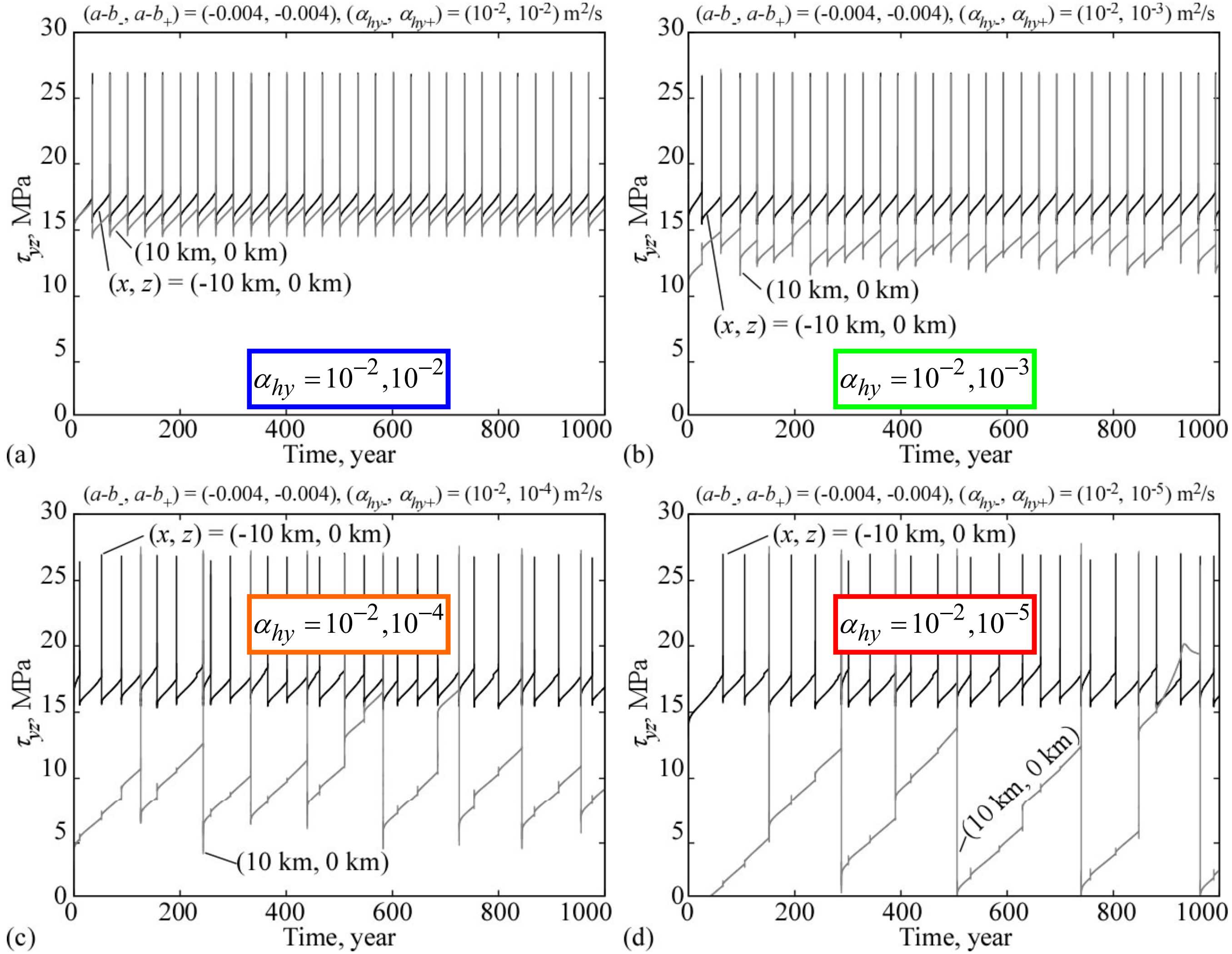
Without heterogeneity, the model produces characteristic events.

Heterogeneity causes long earthquake cycles that contain events of different sizes.

Interseismic shear stress

Shear stress at x = -10 km (black) and 10 km (gray).

$a - b = -0.004$

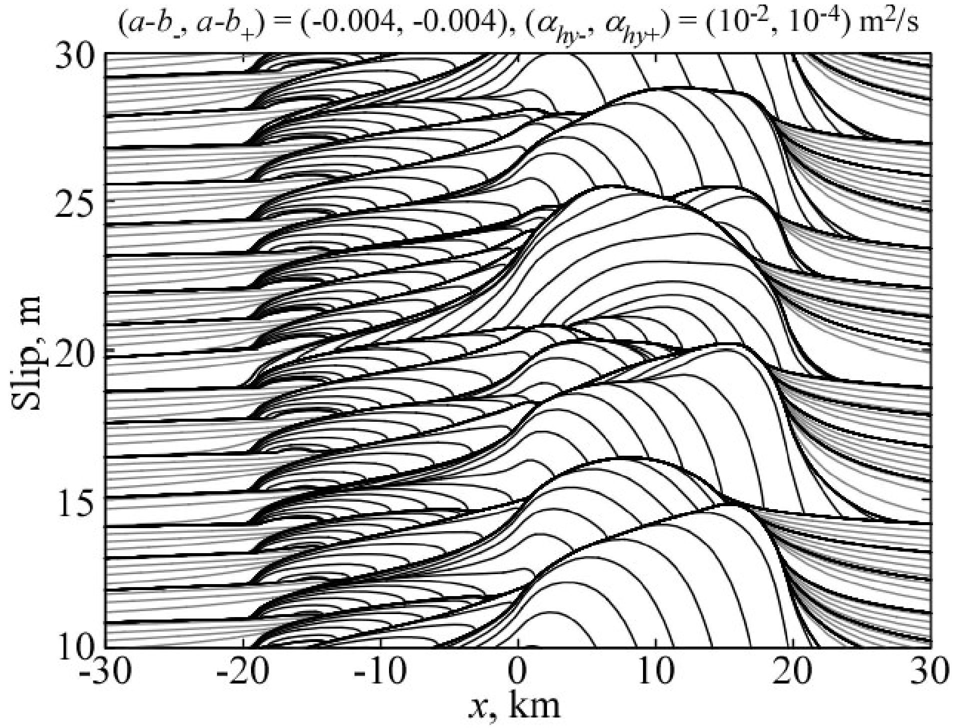


In the region of efficient thermal pressurization, shear stress is lower interseismically due to larger stress drop. That is why events that occur early in the cycle may not propagate into that region.

Nucleation locations on faults with heterogeneous hydraulic dffusivities

Previous studies have shown that fault regions more suscesptible to pore pressurization would promote earthquake nucleation, everything else (such as the initial conditions) being equal [Segall and Rice, 2006].

Our simulations show that such areas may actually be unfavorable for earthquake nucleation due to interseismically lower shear stress.

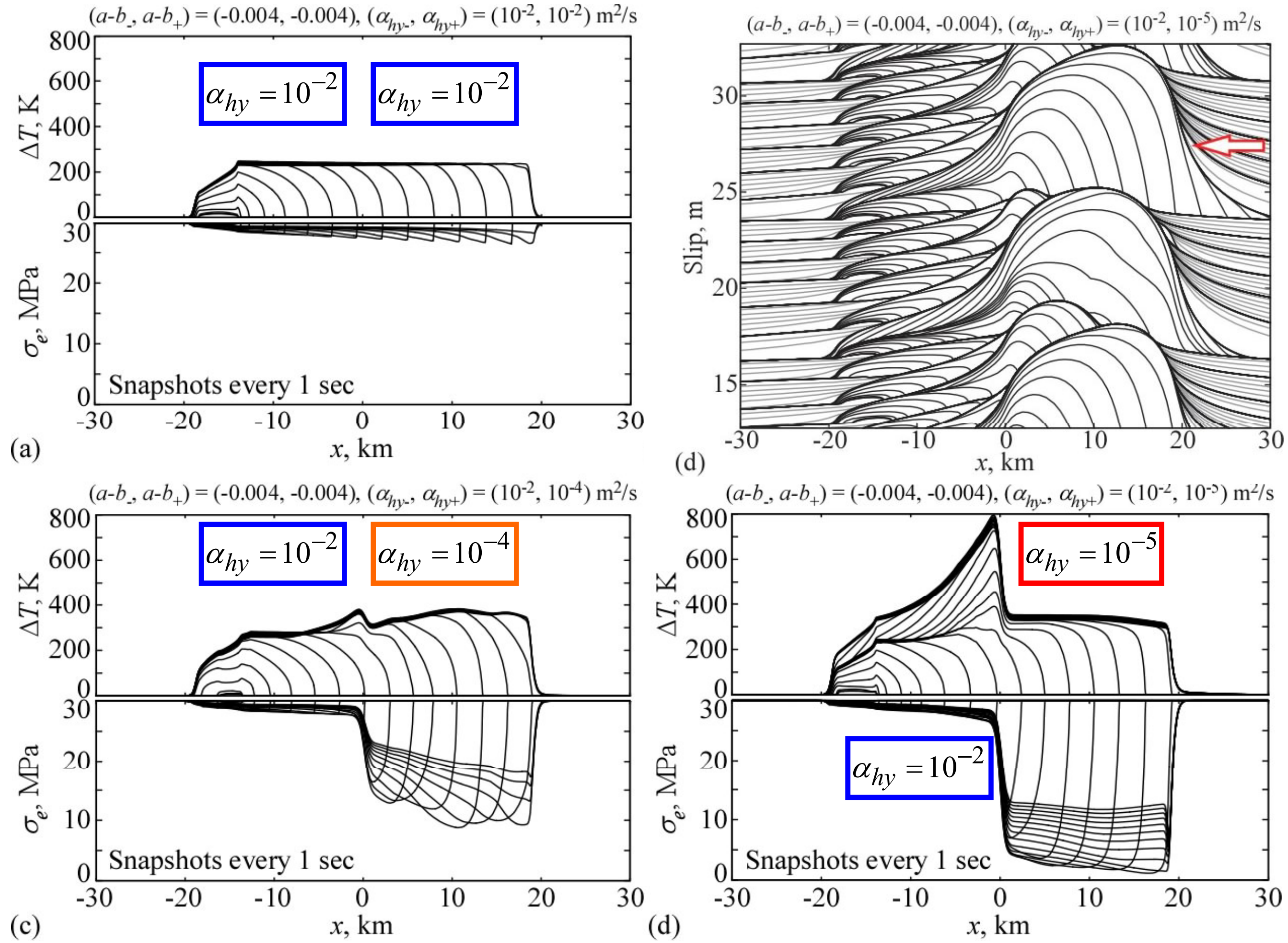


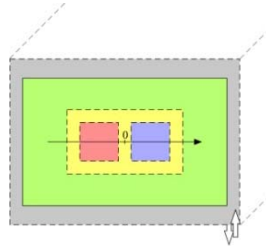
This highlights the importance of considering the effects of fault heterogeneities in the context of earthquake sequences.

Effect of heterogeneity in the hydraulic diffusivity on temperature distribution

Temperature and effective normal stress every 1 sec in a large event at $z = 0$

$a - b = -0.004$

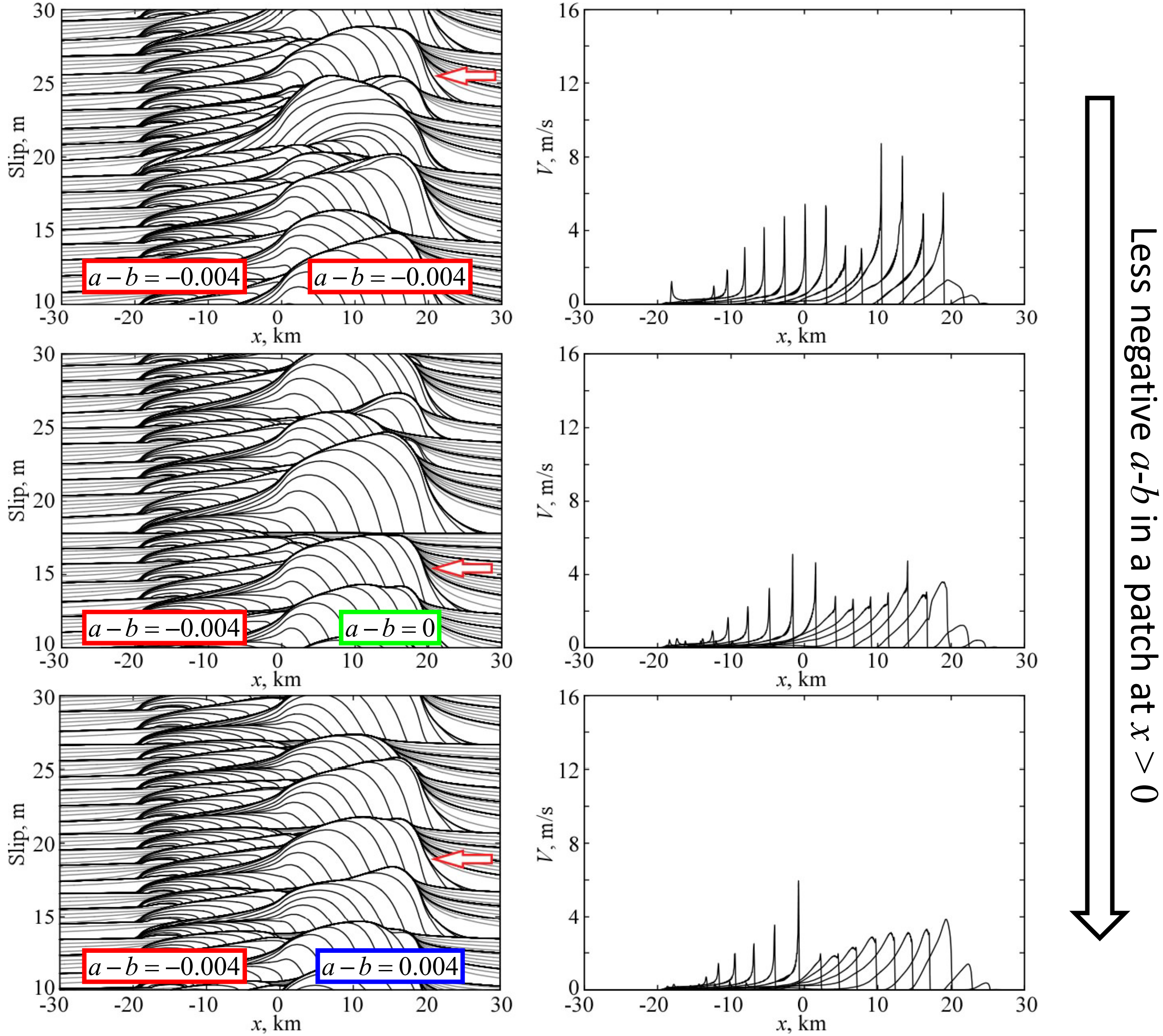




Fault temperature is highest not in the region of the largest slip. The fault area of highest temperature has intermediate level of slip, but high frictional resistance.

Combined effect of rate-hardening and T.P.

$\alpha_{hy} = 10^{-2}, 10^{-4}\,\mathrm{m^2/s}$



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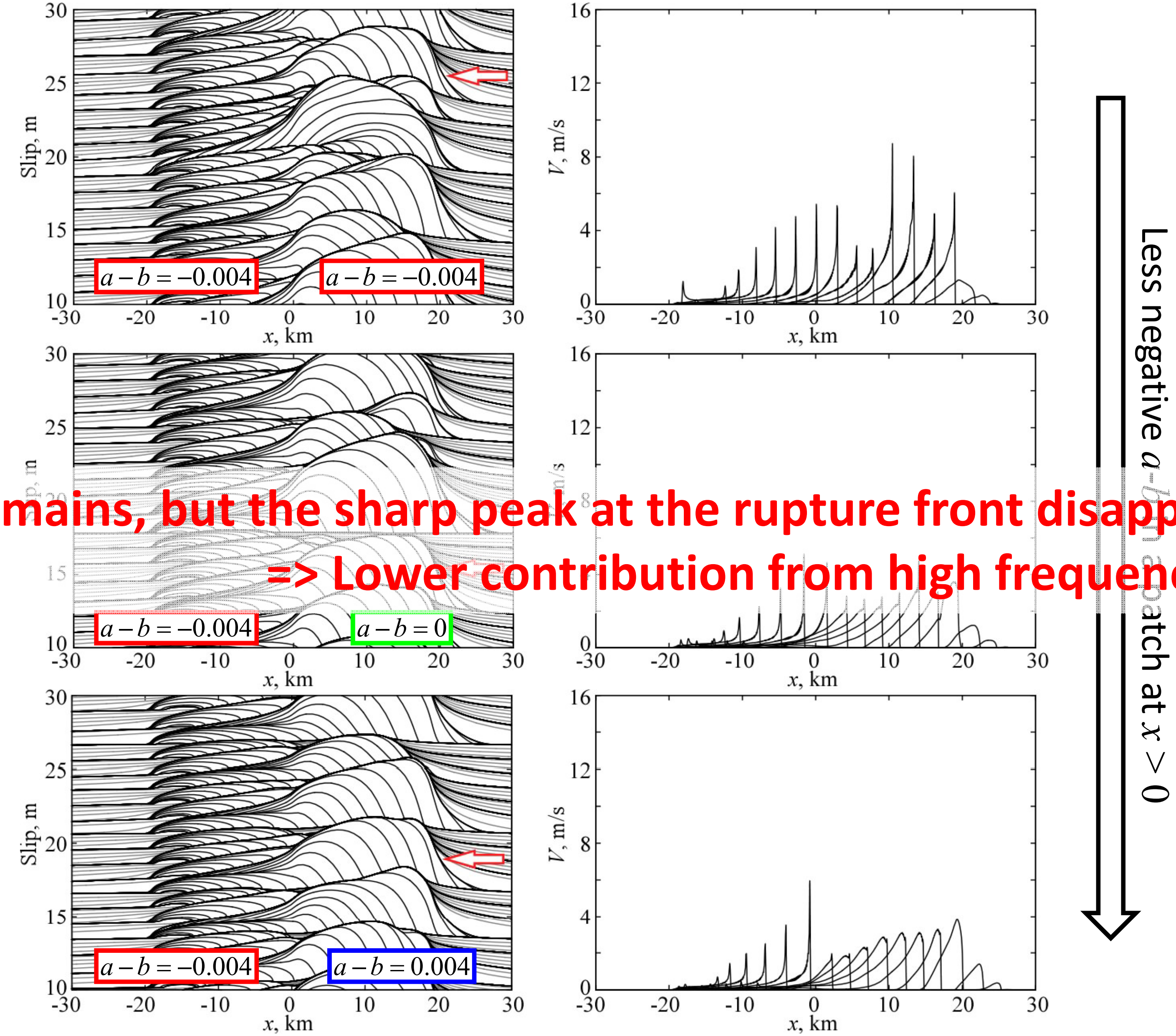

The tail remains, but the sharp peak at the rupture front disappears.

=> Lower contribution from high frequencies!

Conclusions

- We have developed a methodology for simulating earthquake cycles that accounts for the evolution of temperature and pore pressure on the fault and their 1D diffusion off the fault.

- The effect of heterogeneous hydraulic and frictional properties have been examined.

  - The region of more efficient thermal pressurization (TP) has larger slip when it ruptures. Hence it does not rupture in every event.

  - The region of more efficient TP does not nucleate events in our simulations, even though the theoretical estimate [Segall and Rice, 2006] of nucleation size is smaller for such regions. This is due to inerseismically lower shear stress.

  - The highest temperature does not occur in the area of largest slip.

  - Combined effect of TP and rate hardening leads to areas of larger slip having coseismic behavior depleted in high frequencies, similarly to what was observed in 1999 Chi-Chi, Taiwan, earthquake.