Mechanical conditions for propagating a rupture to the surface
The example of the great 2011 Mw 9.0 Tohoku-Oki EQ

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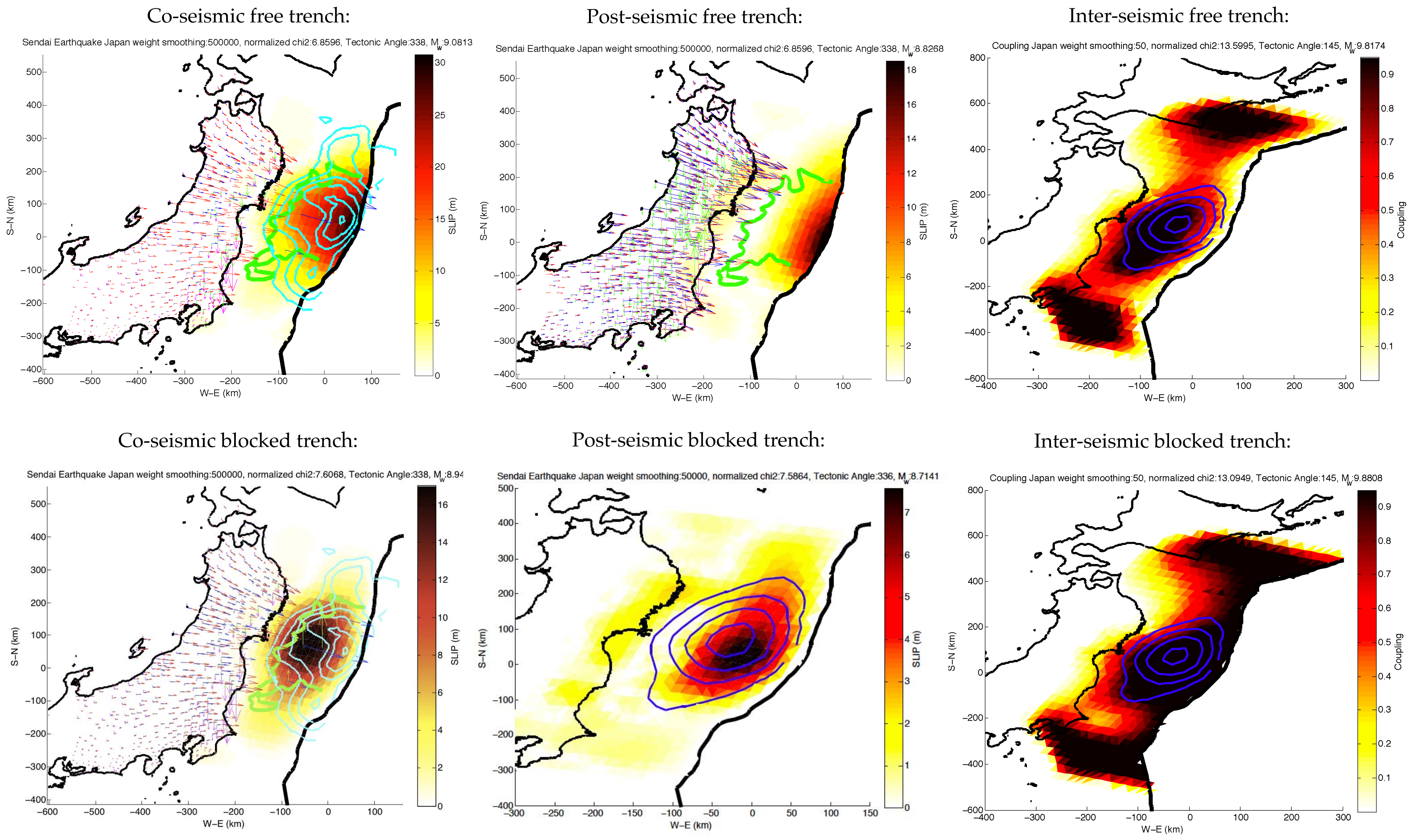
This work has been partly funded by the Gordon and Betty Moore foundation

1. Observations:



Models with 2 different assumptions on the trench: either free or blocked, from Perfettini and Avouac in prep. see poster: Co-, post- and inter-seismic models of the 2011 Mw9.0 Tohoku-Oki EQ. Inter-seismic models are obtained from data compiled by Loveless and Meade, GRL, 2011.
light blue: Wei et al., EPSL (2011) co-seismic model; green: aftershocks delimitation from Kato and Igarashi GRL, 2012; dark blue: co-seismic slip model with assumption of blocked trench.

Co-seismic and post-seismic models were obtained by joint inversion from the displacement of 400 inland stations + 5 sea-floor sites for a period of 279 days after the mainshock by Perfettini and Avouac see POSTER : Co-, post-, and inter-seismic models of the 2011 Mw 9.0 Tohoku-Oki EQ.

Two different boundary conditions were investigated:
>> a free trench (slip is permitted near the trench). In that case, maximum of co- and post-seismic slip are localized at the trench. The co-seismic model fits well with Wei et al. (EPSL 2011) model.

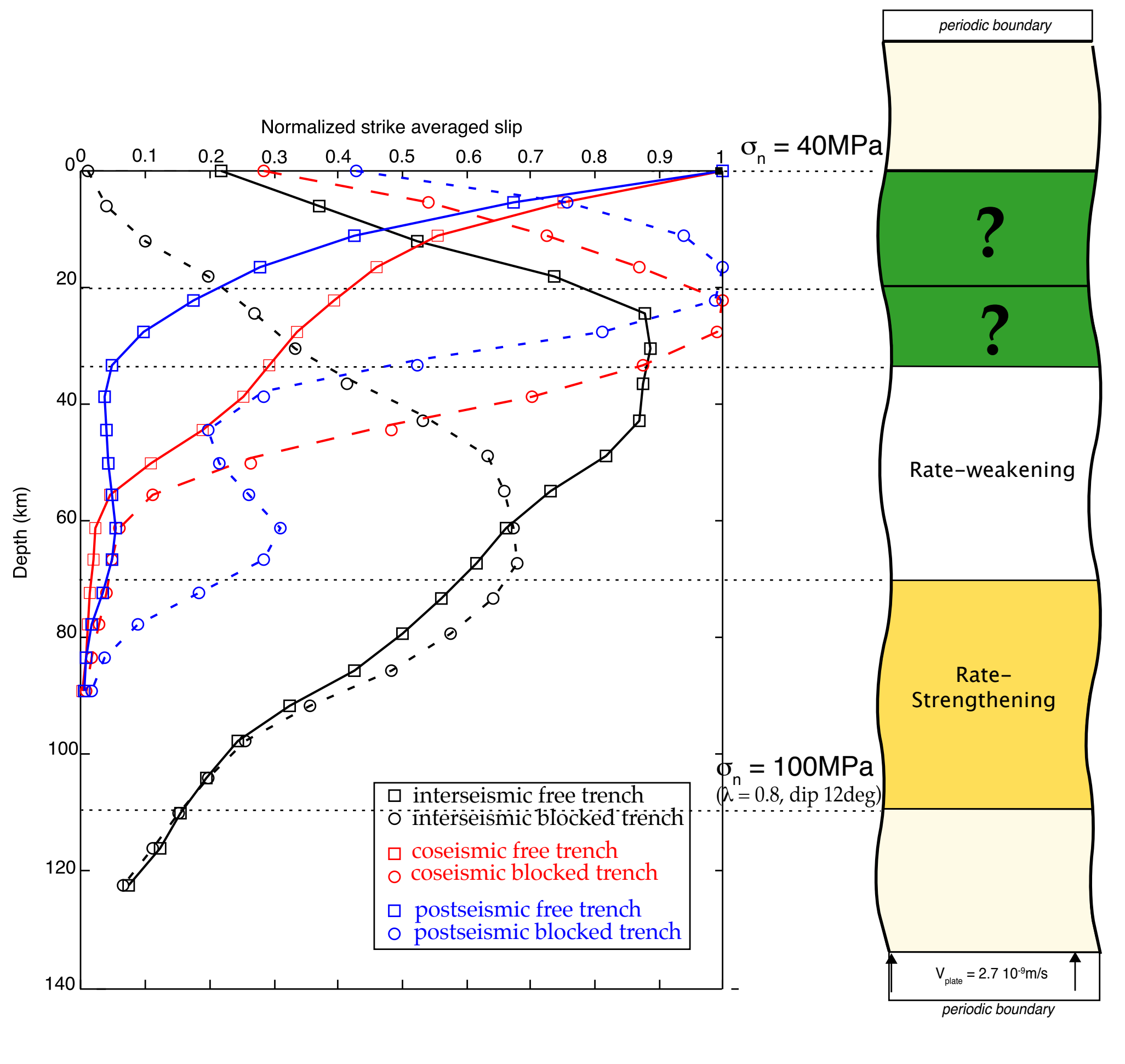
>> a blocked trench (slip is forced to taper to zero near the trench). In that case, the co-seismic and post-seismic slips are superimposed.

Taking different boundary conditions for the co-seismic and post-seismic slip could resolve the superimposition of slip.

In this study, we propose to investigate the mechanical consistency of these different slip models in order to better understand the mechanical conditions allowing for a very large slip near the trench as well as a large post-seismic slip in the up-dip portion of the megathrust.

To do so, 2D dynamic earthquake cycle simulations will be compared to seismic cycle models retrieved from the geodetical studies.

2. Model set-up from observations:



We used 2D dynamic simulation of earthquake cycles based on Lapusta and Liu, JGR 2009 and Noda and Lapusta, JGR 2010 , accounting for inertial effects during seismic events and incorporating:
=>> Rate and state friction laws for low slip rate response: Laboratory derived laws (Dietrich, Ruina, Blanpied, Marone, Tullis, Scholtz and others), unique tool for simulationg earthquake cycle in their entirety

$$\tau = \bar{\sigma} f = (\sigma - p)[f_o + a\ln\frac{V}{V_o} + b\ln\frac{V_o\theta}{L}]; \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

if a-b< 0 : the friction is rate-weakening (RW, nucleation and stick-slip behavior)
if a-b>0: the friction is rate-strengthening (RS)

=>> Thermal pressurization due to frictional heating in a shear zone: Rapid shear heating during seismic slip increases fault temperature which may increase the pore fluide pressure leading to co-seismic fault weakening, additional to any slow-slip friction behavior.

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

Rate- and state- parameters:
$a = 0.1$
$b_{rs} = 0.$
$b_{rw} = 0.014$
$L = 0.004$m
$Vo = 10^{-6}$ m/s
fo varies from 0.3 - 0.5

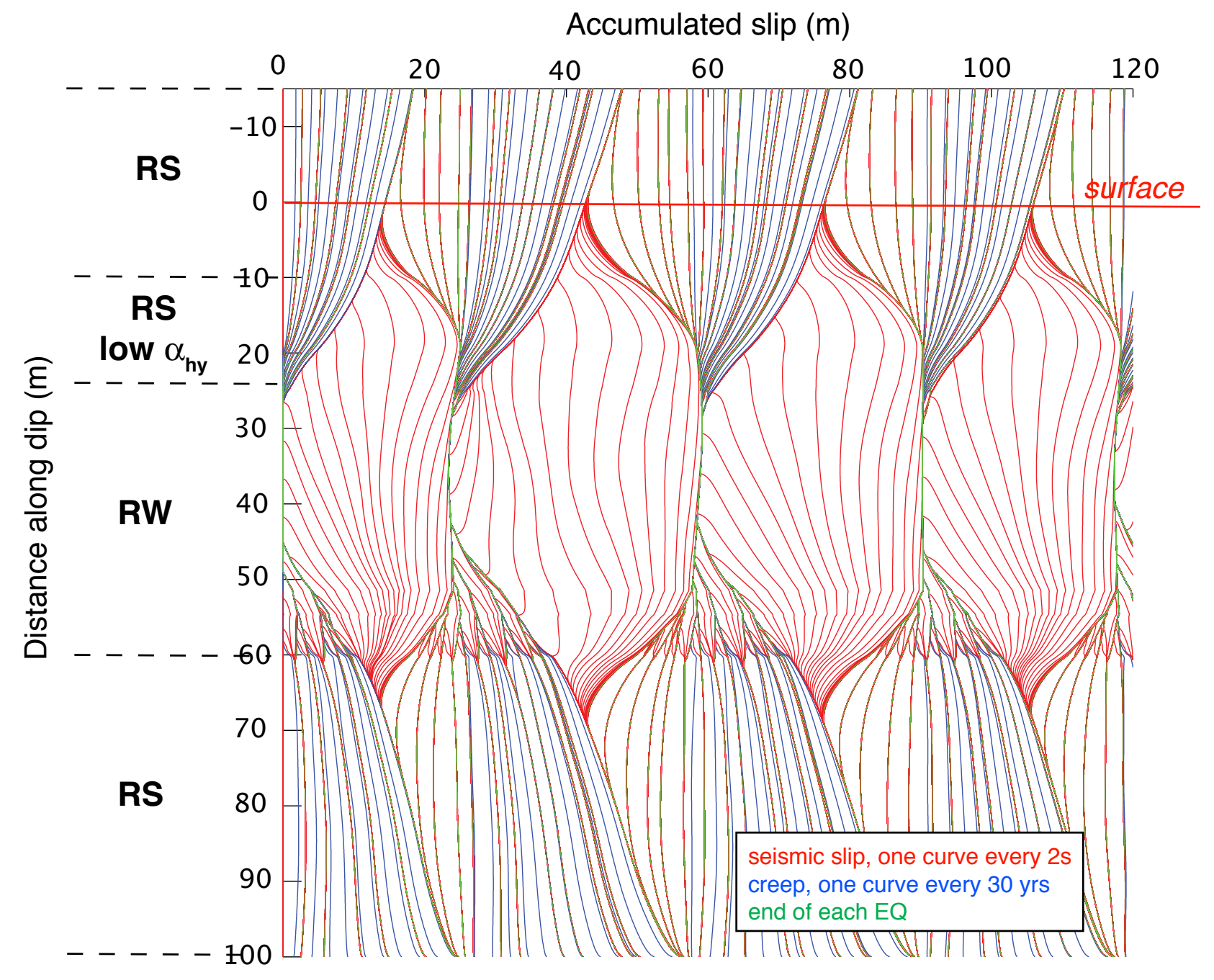
Hydro-thermal parameters:
$\lambda = 10^5$Pa/K
width sz = 10mm
ρ_c = 2.7 MPa?K
α_{th} = 10^{-6} m^2/s
α_{hy} = from 1.10^{-3}m^2/s to 1.10^{-2}m^2/s

In order to understand how to get a large amount of co-seismic slip near the trench as well as the large post-seismic slip, different behaviors of the updip part of the megathrust will be tested :
> either the region is rate-strengthening and undergoes strong weakening by thermal-pressurization as proposed by Noda and Lapusta, Nature, in press, SEE POSTER From stable to destructive: creeping fault segment can join earthquake rupture due to dynamic weakening.
> or the region is conditionally stable (a-b=0)
> or a second rate-weakening asperity lies near the trench separated by a rate-strengthening barrier.

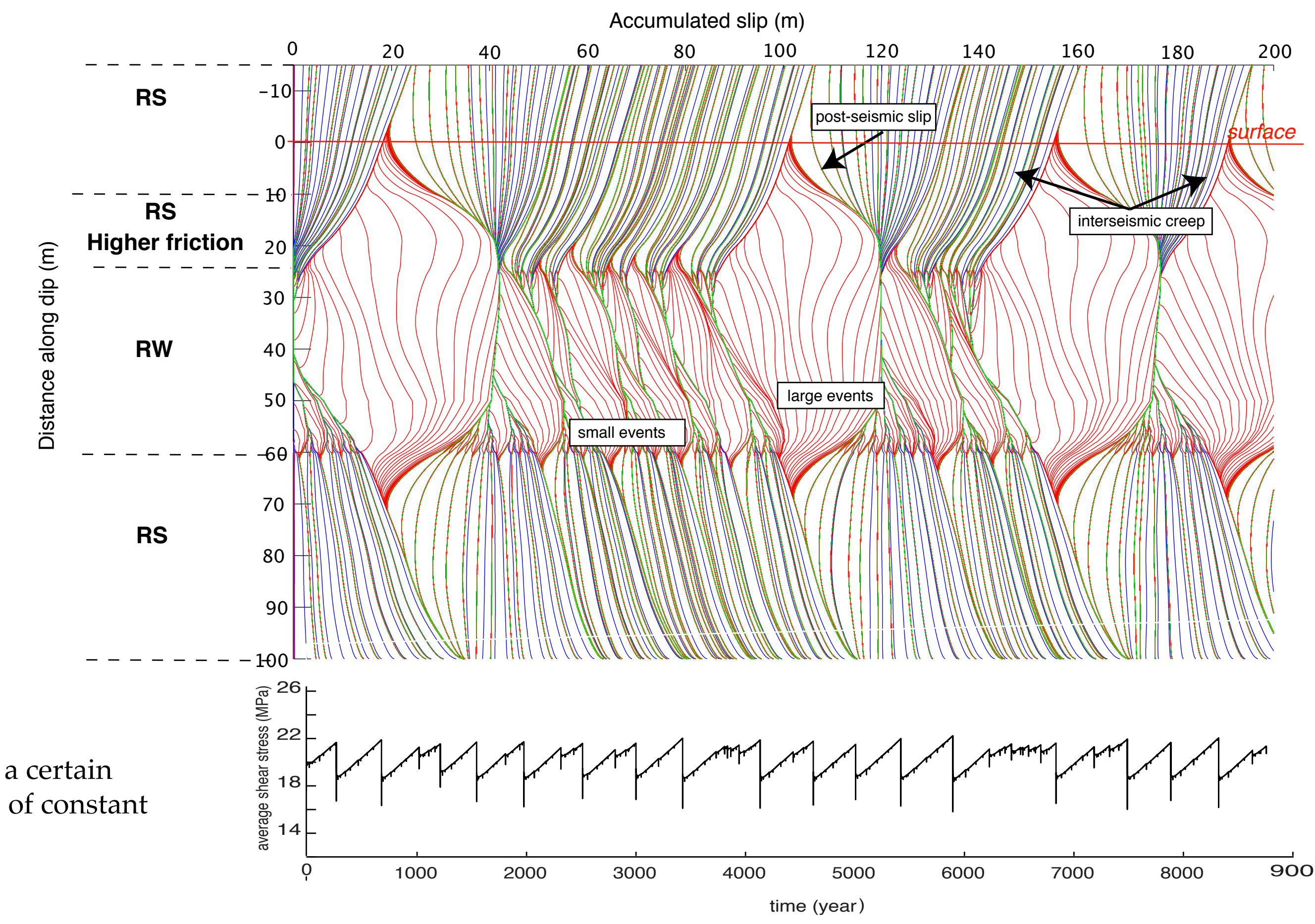
Free surface is thought to increase the amount of slip because of the trapping and concentration of seismic waves (Kozdon and Dunham, subm.). Although the 2D simulations do not include a free surface, the behavior of the region of lowest normal stress can still be qualitatively compared to the observations.

3. Dynamic simulations of earthquake cycles:

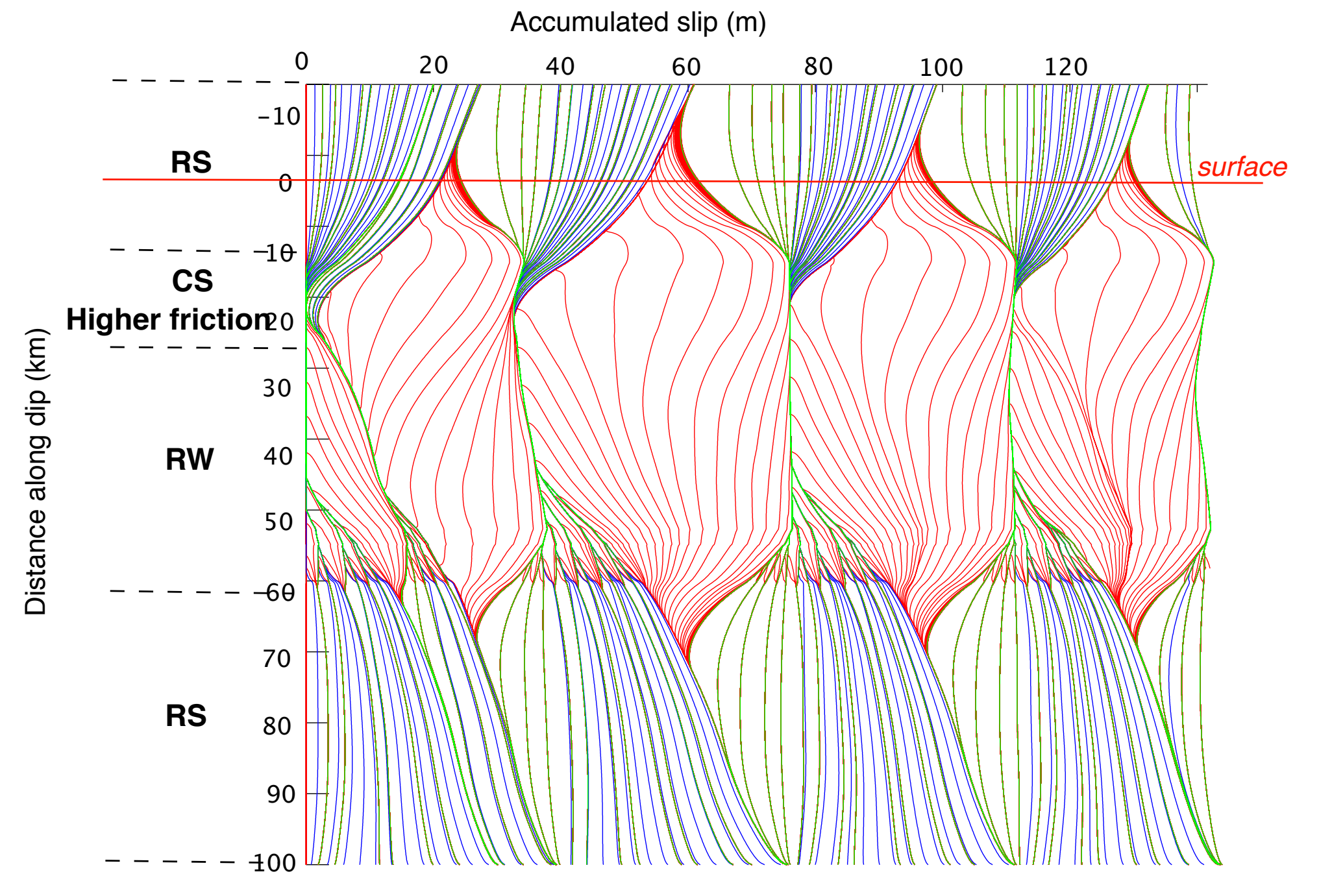
RS with efficient TP



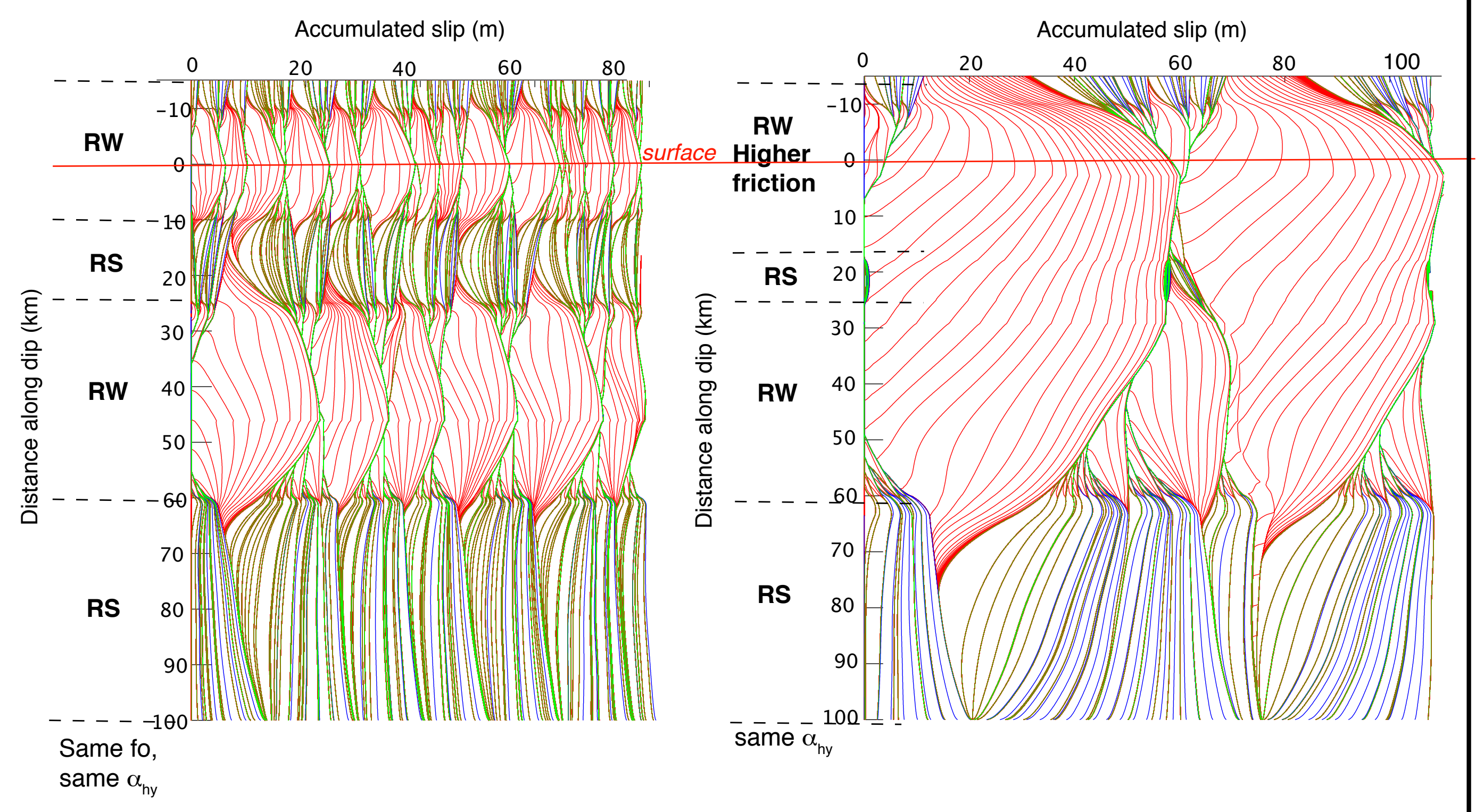
RS with TP + increase of friction



Conditionally stable with efficient TP



RS barrier and 2nd RW asperity:



Co-seismic slip:
to have co-seismic slip in the rate-sterngthening area, we need to reach a certain amount of slip allowing for efficient thermal pressurization. In the case of constant friction and constant slip rate, this slip parameter can be defined as:

$$L^* = \frac{4}{f^2}\left(\frac{\rho c}{\Lambda}\right)^2 \frac{\left(\sqrt{\alpha_{hy}} + \sqrt{\alpha_{th}}\right)^2}{V}.$$

Efficient TP can be achieved by decreasing the permeability or the width of the shear zone or by increasing the friction.
However a trade-off has to be find between a large L* allowing for an unusual propagation in the rate-strengthening area, and a strong shear stress drop allowing for a very large slip.
A large friction combined with a raisonable permeability can reproduce these large events with a maximum of slip localized up-dip and a large reccurence time. A stronger normal stress in the up-dip part of the megathrust could lead to the same results.

Post-seismic:
In order to have a large amount of post-seismic slip at the trench, the coseismic slip has to decrease strongly at the trench. This can be achieved by increasing the permeability at the trench. A higher slip at the trench would not allow for postseismic deformation. Besides, since each large EQ undergoes a backward propagation, a postseismic deformation at the back seems unlikely.

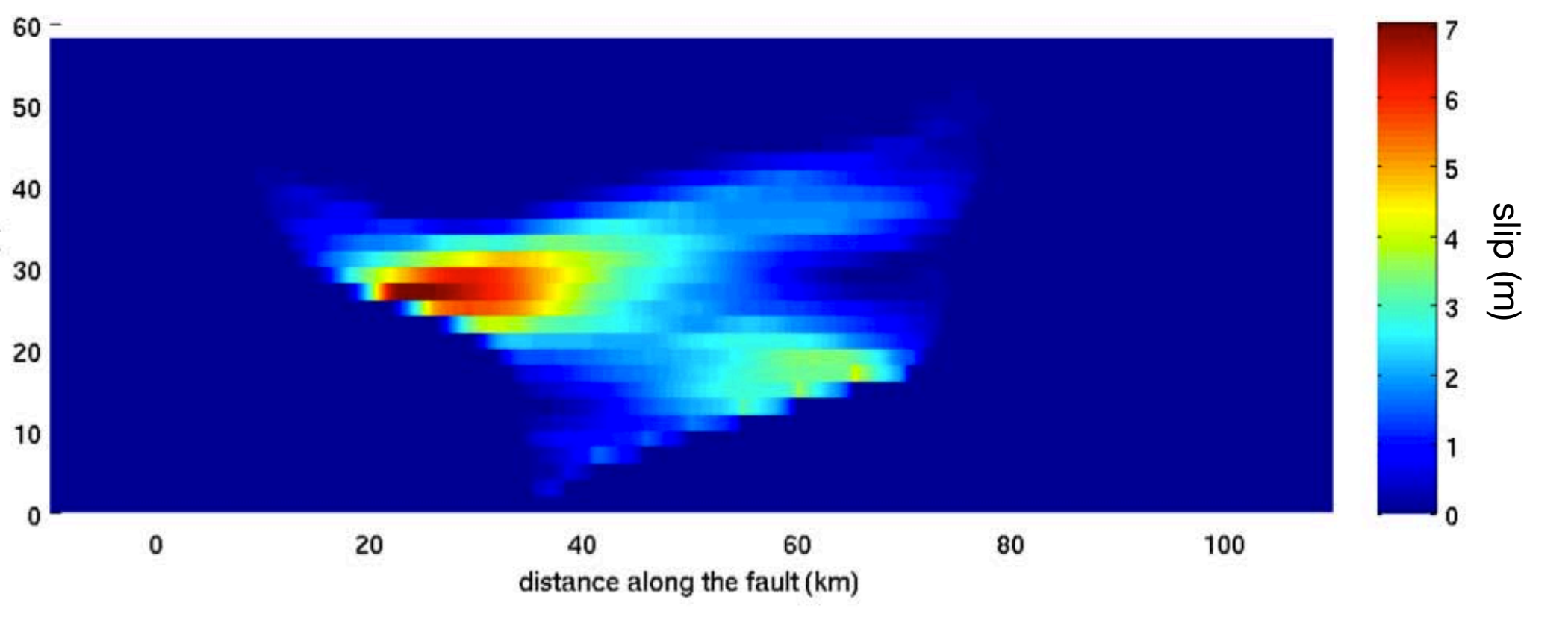
Interseismic:
In case of large reccurence time of the large events, interseismic creep will occur at the trench. If large slip could shoot the interseismic creep, then post-seismic deformation should be limited.

Conditionally stable:
Large slip can also be achieved by thermal pressurization in a conditionally stable patch. The interseismic creep before the EQ as well as the post-seismic slip can also be reproduced. However, the propagation in the up-dip conditionally stable zone is almost systematic.

RS barrier:
As shown by Kaneko et al., Nat. 2009, the propagation through a RS barrier depends on the width of the barrier and the pre-stress. A large EQ could propagate through but neither interseismic creep nor postseismic slip could be observed.

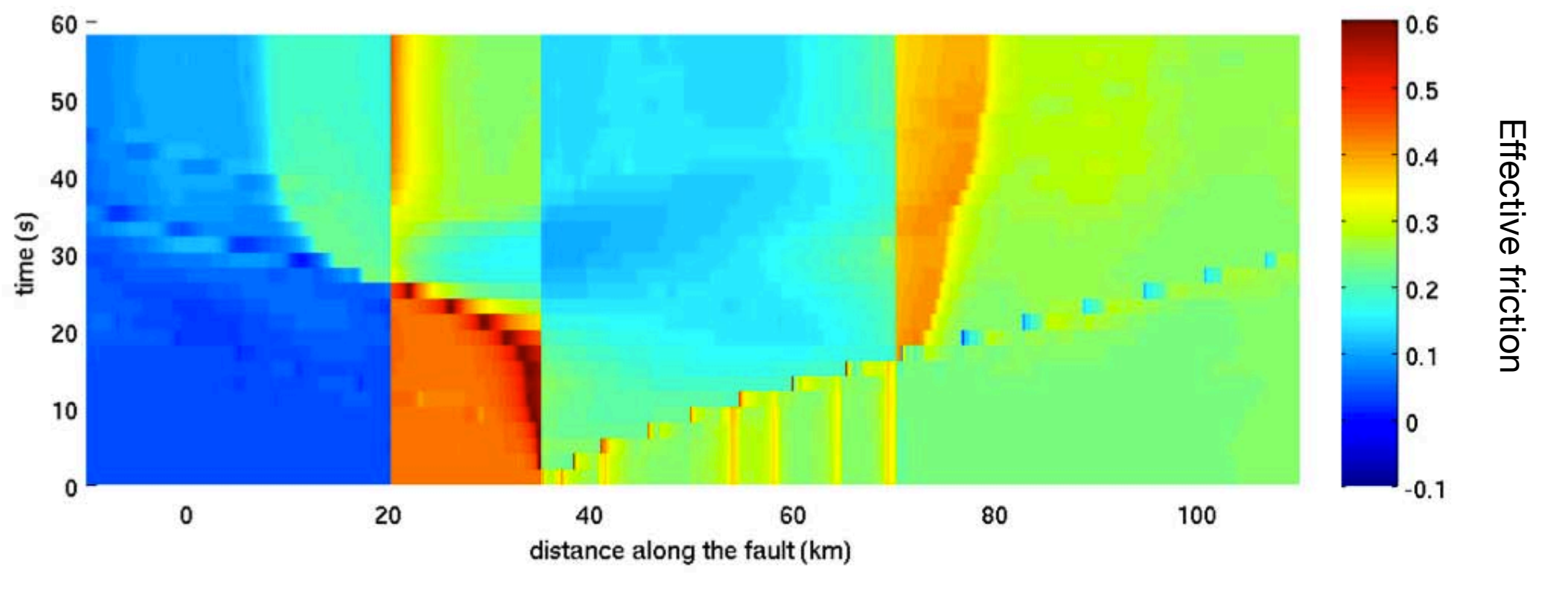
4. Comparison with observations

Backward propagation



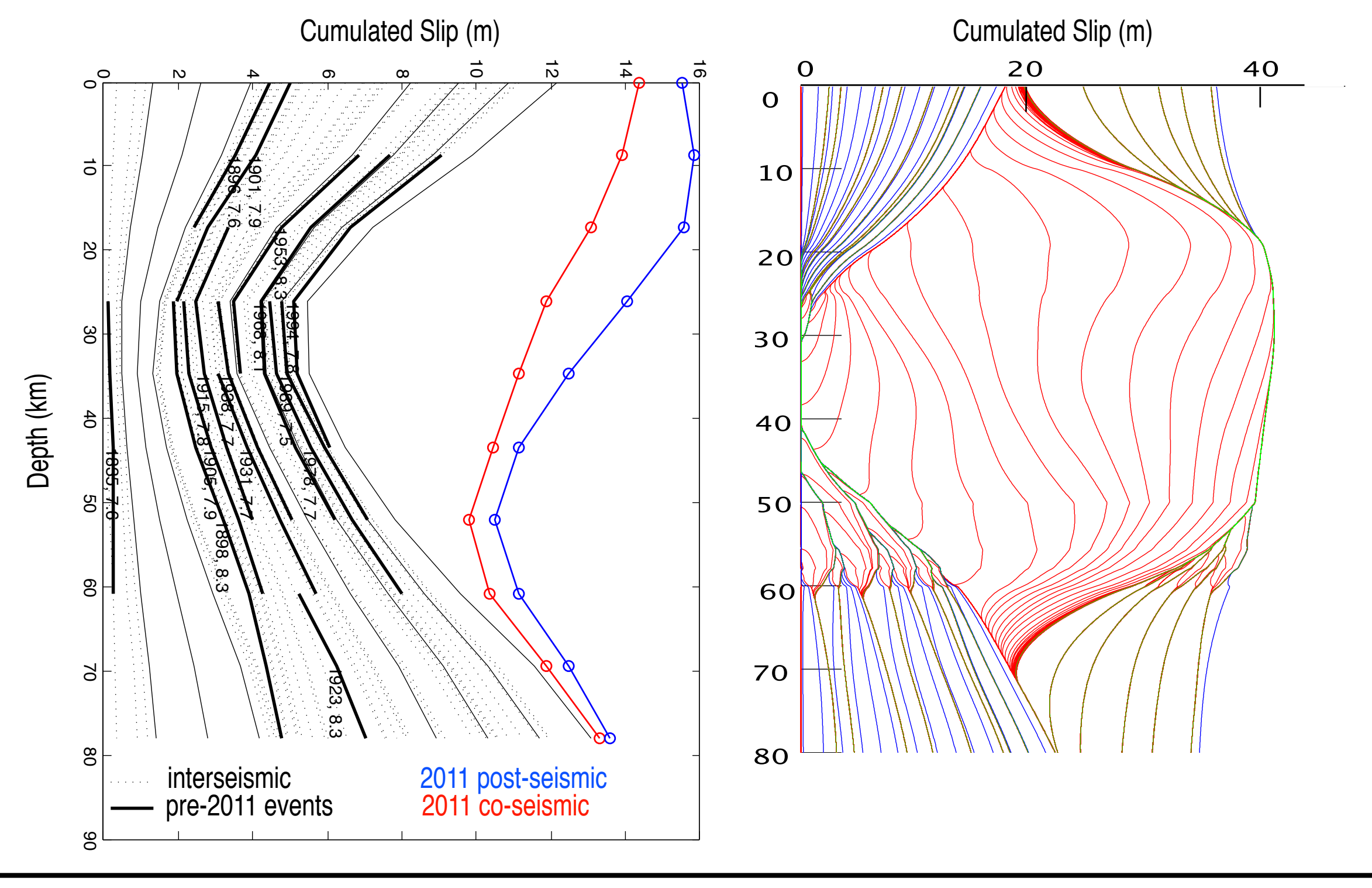
The backward propagation as observed by Meng et al., GRL 2011, is very well reproduced:
The EQ went first down-dip then up-dip and again down-dip.

Effective friction



In the up-dip part of the megathrust, a higher static friction as well as a higher dynamic pore pressure and a low effective dynamic friction are consistent with properties required to activate the landward normal fault (SEE POSTER: Mechanical conditions to activate the landward normal fault of the NE Japan forearc)

Comparison with seismic cycle from observations:



Conclusions

=>> Thermal-pressurization can allow propagation of earthquakes to the trench even though the trench was interseismically non coupled.

=>> Efficient TP can be achieved by a decrease of permeability along the megathrust towards to surface and/or by a sudden increase of static friction.

=>> Conditionally stable or rate-strengthening up-dip zones could both have a very large earthquake like the Tohoku-Oki Mw 9.0 EQ.
However, only a rate-strengthening up-dip patch can explain the whole observed seismic cycle.

=>> Up-dip thermal pressurization can reproduce several particularities of the Tohoku-Oki EQ like the backward propagation.

=>> A sudden increase of friction, decrease of permeability leading to a high pore pressure are also required to activate the landward normal fault.