Fully-dynamic vs Quasi-dynamic simulations of slip accumulation on faults with heterogeneous friction properties

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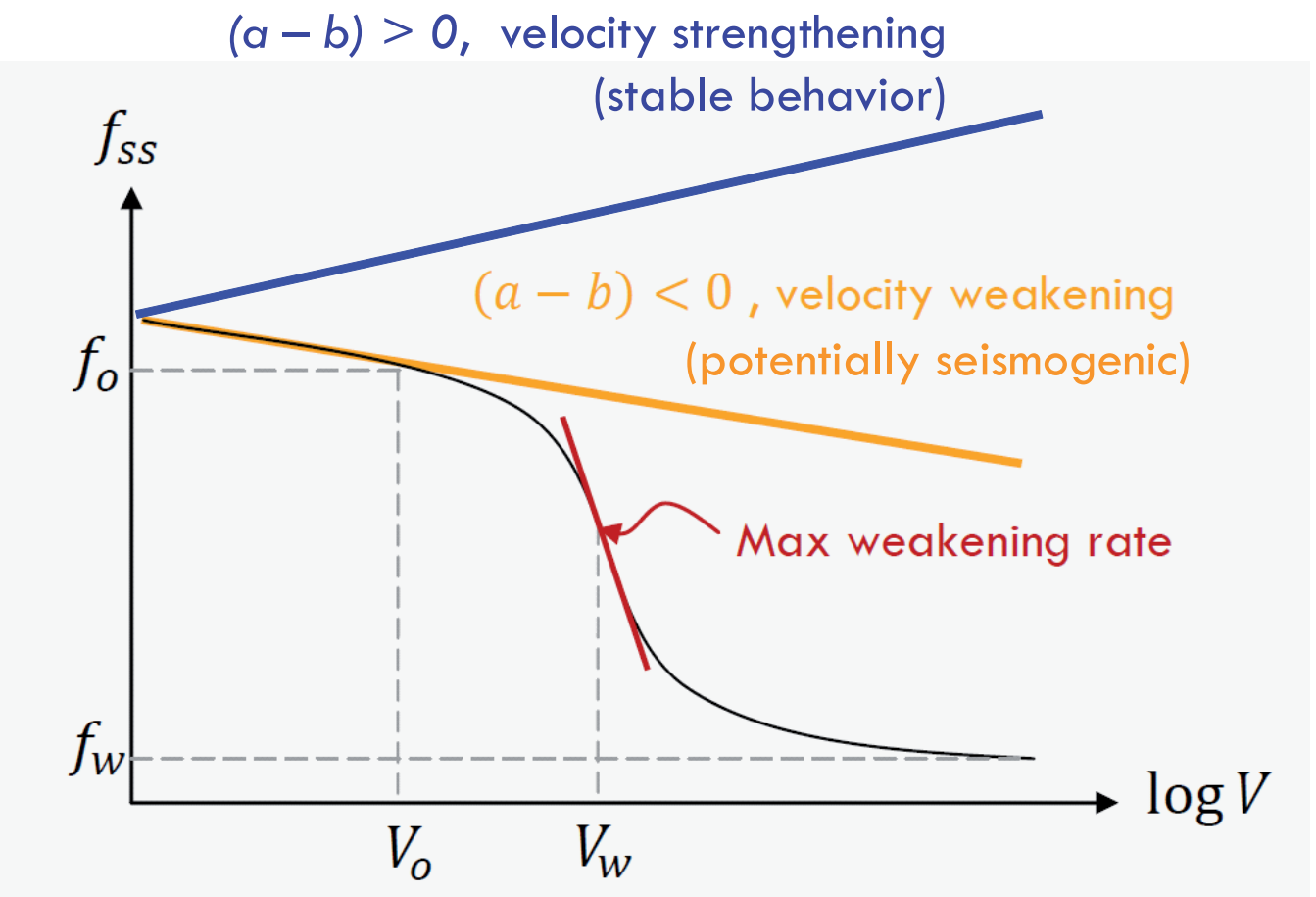
Abstract

A number of factors which might be inferred from geological and geodetic observations are thought to influence fault seismic behavior: they include lithology which might control mechanical properties of fault zone, pore pressure and faults geometry. In theory the imfluence of these factors might be estimated from theoretical fault models and computer simulations. This is computationally challenging because this kind of study requires a proper account of the effect of these factors on rupture dynamics, at the scale of individual seismic event, as well as long sequence of rupture to capture the stochastic behavior of faults systems. In such studies it is computationally advantageous to not incorporate full inertial effects during simulated fast slip. That is why so-called quasi-dynamic methods have become increasingly popular, which approximately account for inertial effects (and hence seismic radiation) during simulated earthquakes through a radiation damping term. Such methods allow continuing simulations through the seismic phase, without having to pay significant additional memory and computational costs associated with modeling true wave-mediated effects. However, the resulting seismic events tend to have much slower slip velocity and rupture speeds and may modify significantly the resulting seismic events and hence the long-term fault behavior.

In this study, we compare the results of quasi-dynamic and fully dynamic simulations, with wave effects during simulated earthquakes. We consider the long-term fault behavior in two problems: (i) interaction of two velocity-weakening regions separated by a small velocity-strengthening patch and (ii) segments with additional pronounced rate-weakening during seismic slip. We find that, in the absence of additional seismic weakening, the two methods generally result in the same qualitative behavior, with similar slip patterns, although there are quantitative differences. However, in simulations with additional rate weakening, the two methods produce qualitatively different long-term results, with different slip patterns and significantly different levels of shear stress on the fault. Our eventual goal is to determine the range of applicability for the quasi-dynamic approaches.

Numerical model statements

(a) Rate-and-state law with or without additional weakening



Allows simulating earthquake cycles their entirety,

from accelerating slip in slowly expanding nucleation zones
to dynamic rupture propagation
to post-seismic slip and interseismic creep
to fault restrengthening between seismic events.

In those models we are using laboratory derived friction laws.

$$\tau = \bar{\sigma}\left(f_0 + a\ln\frac{V}{V_0} + b\ln\frac{V_0\theta}{L}\right) = \bar{\sigma} f_{R\&S}$$

The parameters “a” and “b” in this equation allow describing 2 kind of material:

(a-b)>0: the friction increase with velocity, so no instabilities occurs and we reach a stable sliding. It is called the velocity strengthening behavior

(a-b)<0: the friction decrease with velocity, so an acceleration occurs, that lead to instability. It is called the velocity weakening behavior and it is potentially seismogenic

R&S law is valid at low velocity. At seismic velocity, some additional weakening mechanism, like flash heating, can help the rupture to propagate.

$$\tau = \bar{\sigma}\left(\frac{f_{R\&S}-f_w}{1+\frac{L}{V_w\theta}} + f_w\right)$$

(b) Quasi-dynamic versus Fully-dynamic modeling

To solve the equations, model uses a Spectral Boundary Integral Method

$$\underbrace{\tau(x,t)}_{\text{Shear stress}} = \underbrace{\tau^o(x,t)}_{\text{loading}} + \underbrace{\boxed{f(x,t)}}_{\text{Stress transfer}} \underbrace{- \frac{\mu}{2c}V(x,t)}_{\text{radiation term}}$$

Evolution of stress in space and time

$$f(x,t) = \sum_{n=-N_{ele}/2}^{N_{ele}/2} \underbrace{\boxed{F_n(t)}}_{\text{Stress transfer in Fourier Domain}} e^{ik_n x} \quad \text{with} \quad k_n = \frac{2\pi n}{\lambda} \qquad \underbrace{\delta(x,t)}_{\text{previous slip}} = \sum_{n=-N_{ele}/2}^{N_{ele}/2} D_n(t) e^{ik_n}$$

Equation in Fourrier Domain

Evolution of stress during the rupture:

$$\underbrace{\boxed{F_n(t)}}_{\text{Stress transfer}} = \underbrace{-\frac{\mu|k_n|}{2}\overset{\sim\text{ slip}}{D_n(t)}}_{\text{Final static elastic stress}} + \underbrace{\frac{\mu|k_n|}{2}\int_0^{T_w} W(|k_n|ct')\,\overset{\sim\text{ slip rate}}{\dot{D}_n(t-t')}\,dt'}_{\text{Wave-mediated stress transfer}}$$

Quasi-dynamic formulation:
Stress transfer = Final static elastic stress

Fully-dynamic formulation:
Stress transfer = Final static elastic stress + Wave-mediated stress transfer

Regular Rate-and-State law

Two models are qualitatively similar but quantitatively different

Figures Captions:

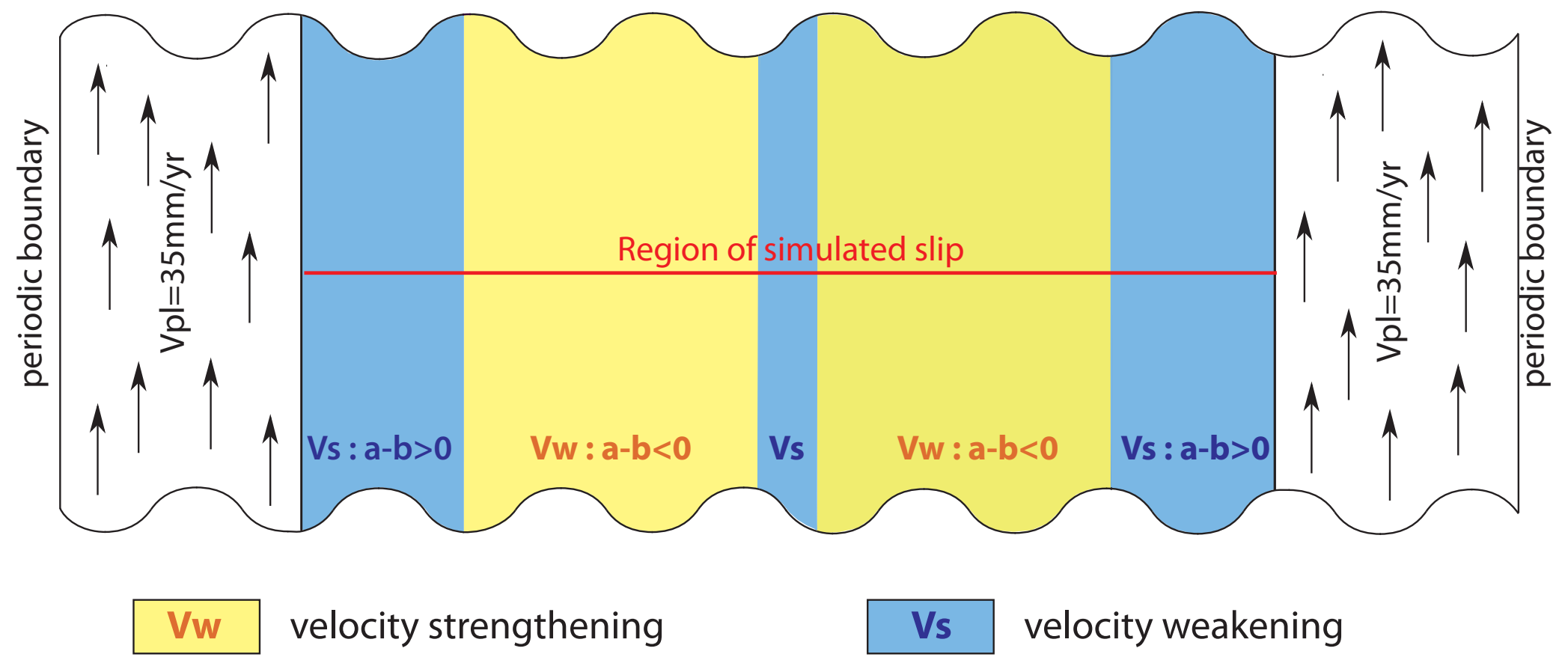
Figure (a): Model
- 2D antiplane model with 1D fault,
- Equations solved for an infinite, uniform, isotropic, elastic space,
- 2 velocity-weakening patches separated by 3 velocity-strengthening patches.

Figure (b): Slip velocity
- Fully-dynamic simulations give larger amount of slip per event,
- Sliding velocity is higher in fully-dynamic model than in quasi-dynmaic model,
- More events are required in quasi-dynamic simulations to accumulate the same amount of slip.

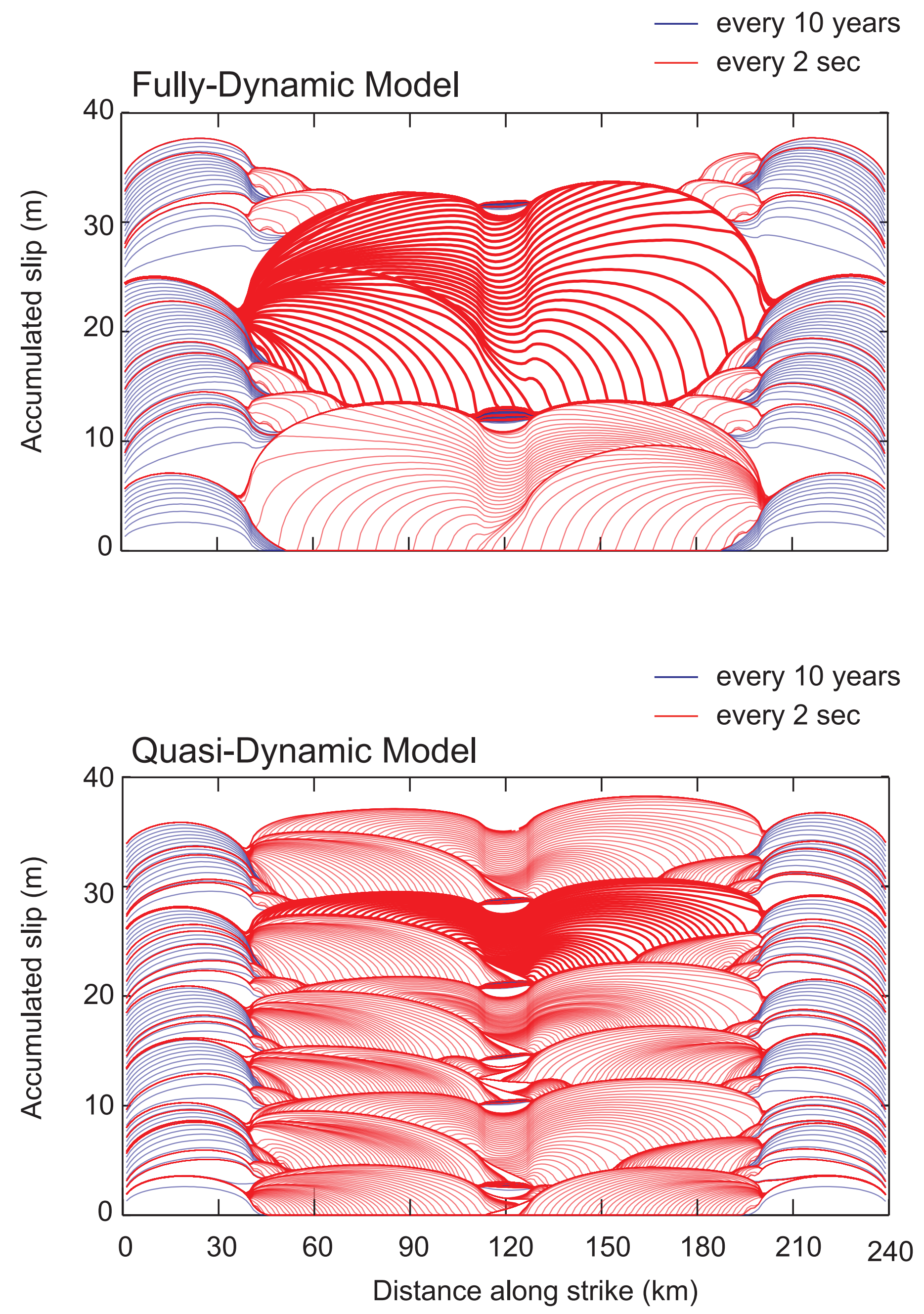
Figure (c): Effect of variations of fault frictional properties
- With the fully-dynamic solution, rupture propagates more easily through the patch VS,
- But overall rupture pattern is similar for fully-dynamic and quasi-dynamic simulations.

(a) Model

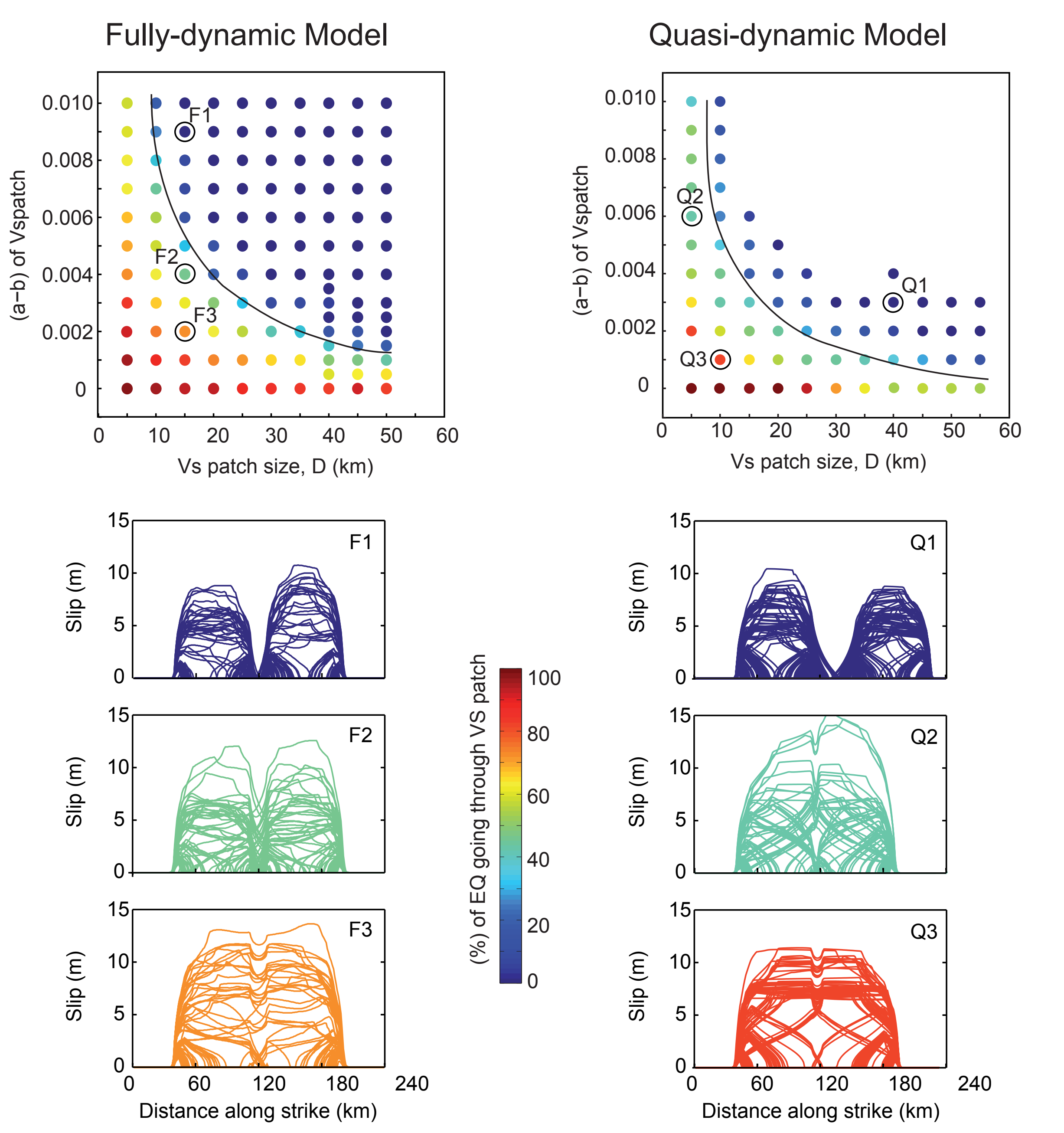
friction law: $\tau = \bar{\sigma}\left(f_0 + a\ln\frac{V}{V_0} + b\ln\frac{V_0\theta}{L}\right) = \bar{\sigma} f_{R\&S} \qquad \dot{\theta} = 1 - \frac{V\theta}{L}$



(b) Slip history



(c) Effect of variations of fault frictional properties



Rate-and-State law with additional weakening

Two models are qualitatively different

Figures Captions:

Figure (a): Model
- 2D antiplane model with 1D fault,
- Equations solved for an infinite, uniform, isotropic, elastic half-space,
- 1 Velocity-weakening patch surrounded by 2 velocity-strengthening patches.

Figure (b) : Maximun slidding velocity
- Max Velocity during events is higher in FD model than in QD model.

Figure (c): Slip velocity
- All events propagate to the end of the velocity-weakening region in FD model.
- Events are more “pulse-like” in FD model, and more "crack-like" in QD model.

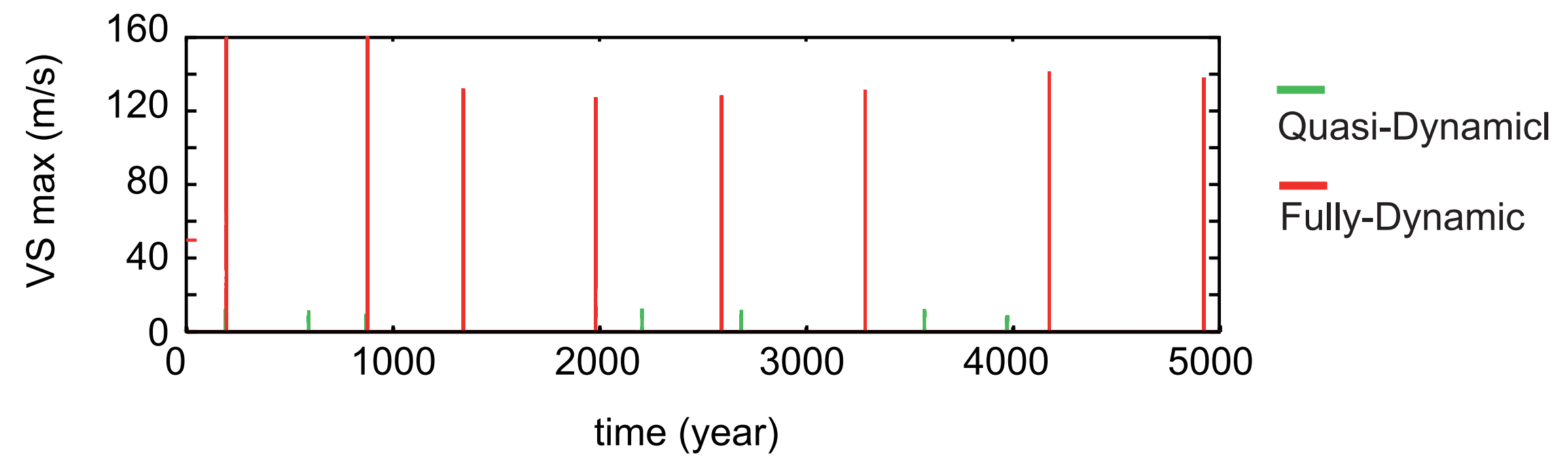
Figure (c) : Average Stress drop
- Average stress, needed for the rupture to propagate, is smaller in the FD models.

(a) Model

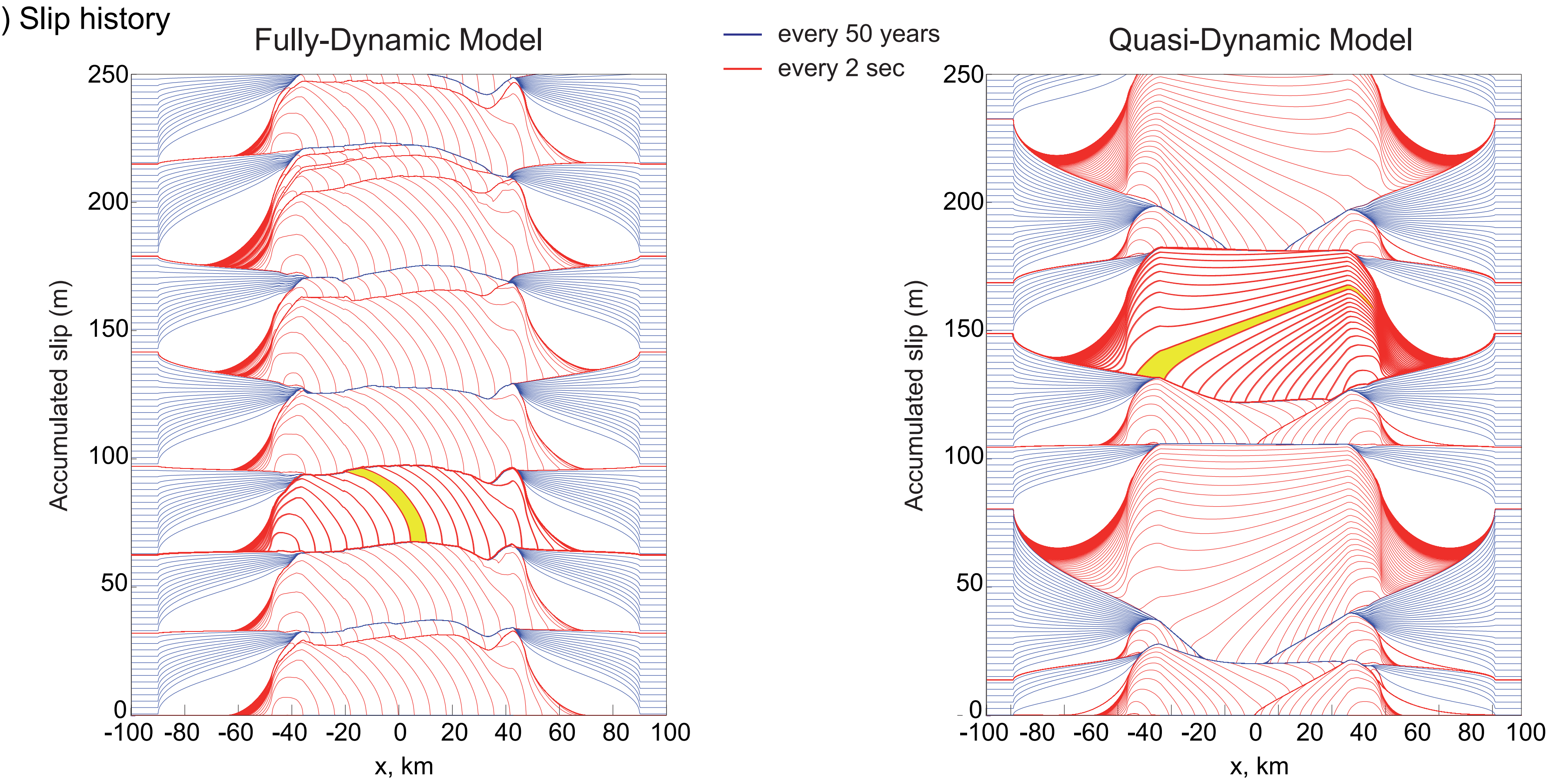
friction law: $\tau = \bar{\sigma}\left(\frac{f_{R\&S}-f_w}{1+\frac{L}{V_w\theta}} + f_w\right)$

we are using a similar geometry, that for the regular R&S law, without the middle VS patch

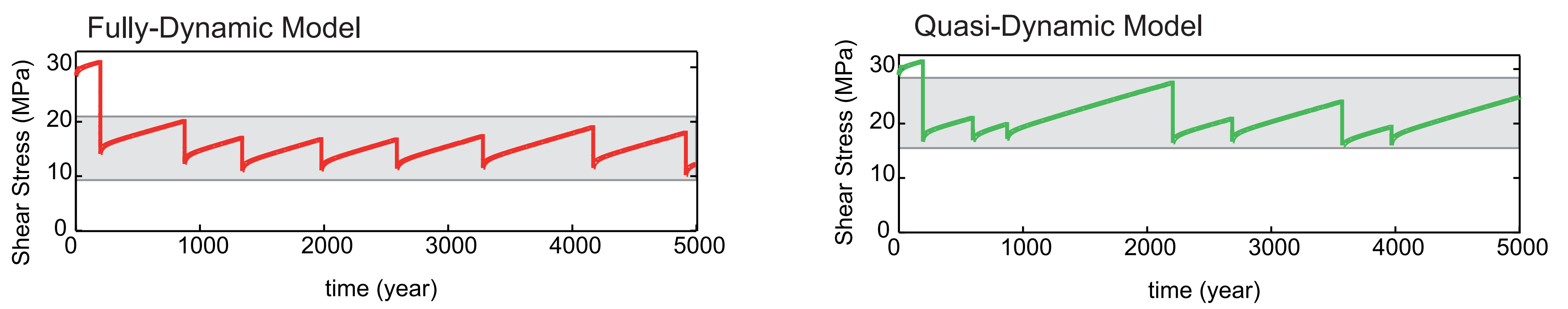
(c) Maximum Slidding Velocity



(c) Slip history



(c) Stress Drop



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