Fully-dynamic vs Quasi-dynamic models to simulate Earthquake cycle

Marion Thomas(1), Nadia Lapusta(1), Hiro Noda(1), Yoshi Kaneko(1)

(1) Tectonics Observatory, California Institute of Technology, Pasadena, CA, USA.

Abstract

Laboratory experiments and theories of how fault materials behave suggest that the constitutive response of faults is far from simple. Observations of seismic events also suggest complex interaction inside fault systems: while one can identify segments on the fault interfaces that tend to fully rupture in the same event, often such segments rupture jointly with neighboring segments producing larger earthquakes. Moreover, we observe that sometimes, earthquakes nucleate but are inhibited, or even arrest when the rupture front encounters patches with velocity strengthening (VS) friction, or patches with low average stress. Theoretical fault models and computer simulations of fault slip can reveal the role and relative importance of different factors on the manner in when / how does the rupture propagate during faulting. In this project we study the importance of the wave-mediated stress in propagating the rupture. For that purpose, we first explore the effect of friction heterogeneities (patches of VS and velocity-weakening (VW)) on the pattern of seismic rupture using a laboratory-derived rate-and-state friction formulation. We compare the seismic pattern obtained from the fully-dynamic formulation (including wave-mediated stress transfer) with the one obtained from the quasi-dynamic formulation. Then, rate-and-state friction law has been modify to allow more variations in frictional strength. For fast sliding velocities and large slip, additional weakening mechanisms result in much lower frictional resistance during sliding. That allows rupture to propagate in the environment of low average stress. Fully-dynamic versusquasi-dynamic seismic pattern have been also compared.

So far, our results show that in the case of regular rate-and-state law, the overall rupture pattern is similar for fully dynamic and quasi dynamic simulations. In contrary, for a rate-and-state law with additional weakening mechanism, we obtained a significant differences between the two models, which needs to be explored more deeply.

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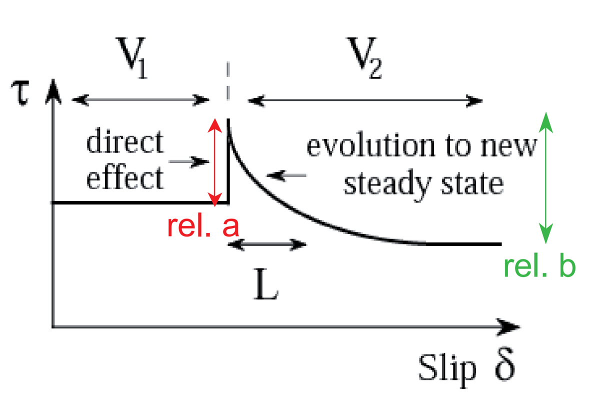
Quasi-dynamic versus Fully-dynamic models: differences

(a) Rate-and-state law



Velocity-jump experiments from Dieterich (1979,81,94) and Ruina (1980,83) show that :
- friction depends on sliding rate,
- changes in slip rates are followed by a transient adjustment.

First response of an increase of velocity is an increas of the friction (illustrated by the parameter "a" in the rate-and-state law).

Then depending on the materials properties, the friction drops to a smaller or higher value than before the velocity jump (illustrated by the parameter "b" in the rate-and-state law)

θ is the state variable that discribes the fault behavior.

Unique tool for simulating earthquake cycles in 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.

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

$$\dot{\theta} = 1 - \frac{V\theta}{L}$$

(b) Quasi-dynamic versus Fully-dynamic firmulations

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

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

Evolution of stress in space and time

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

Stress transfer in Fourier Domain

Equation in Fourrier Domain

Evolution of stress during the rupture:

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

(~ slip; ~ slip rate)

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

Figures Captions:

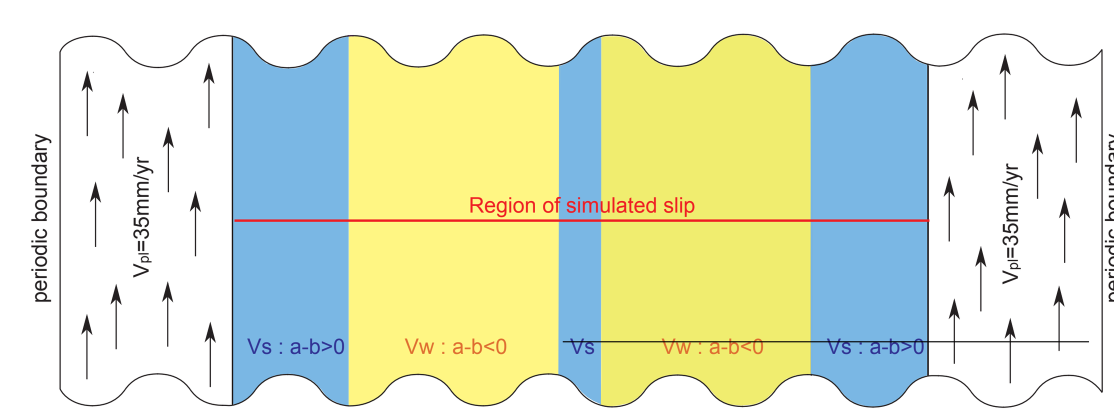
Figure (a): Model
- 2D antiplane model with 1D fault,
- Equations solved for an infinite, uniform, isotropic, elastic space,
- 2 velocity-weakening patches and 3 velocity-strengthening patches.

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.

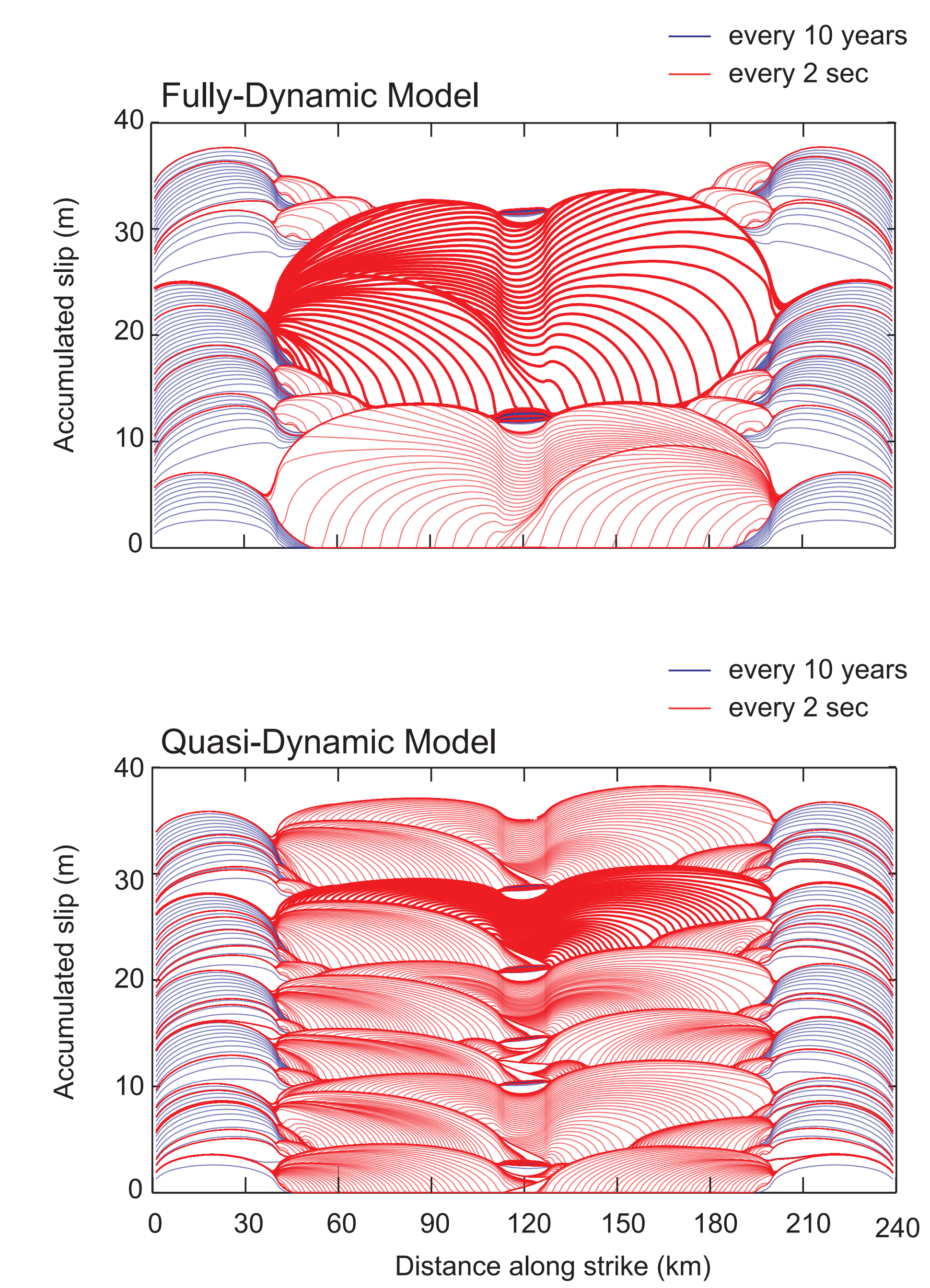
Figure (c): Effect of variations of fault frictional properties
- With the fully-dynamic solution, rupture propagates more easily through the patch VS,
- But overall rupture pattern is similar for fully-dynamic and quasi-dynamic simulations.

(a) Model

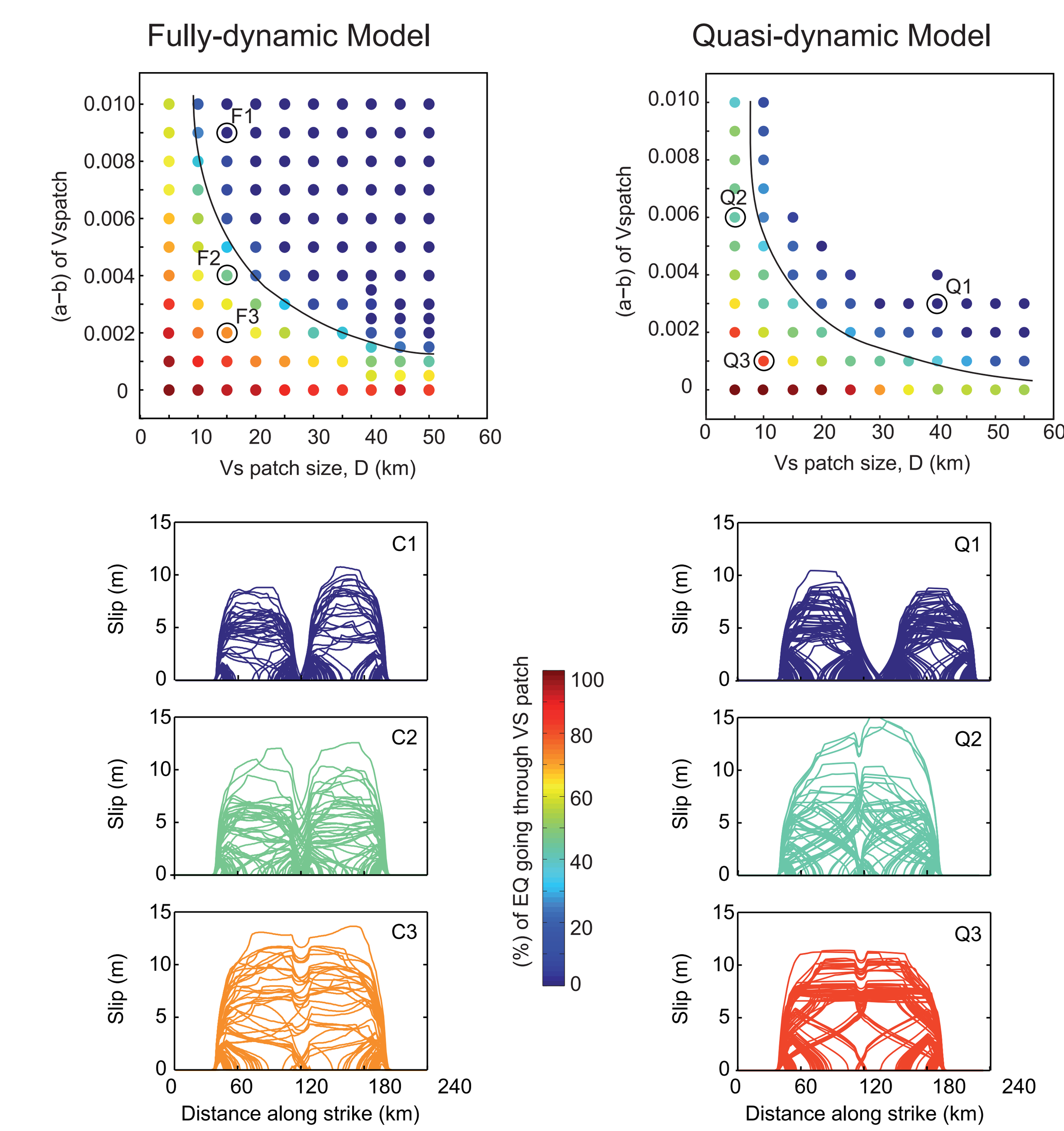
friction law: $\tau = \bar{\sigma}\left(f_0 + a\ln\frac{V}{V_0} + bn\frac{V_0\theta}{L}\right) \qquad \dot{\theta} = 1 - \frac{V\theta}{L}$



(b) Slip history



(c) Effect of variations of fault frictional properties



Rate-and-State law with additional weakening

Figures Captions:

Figure (a): Model
- 2D inplane model with 1D fault,
- Equations solved for an infinite, uniform, isotropic, elastic half-space,
- 1 vVelocity-weakening patch (with weaker zone) and 2 velocity-strengthening patches.

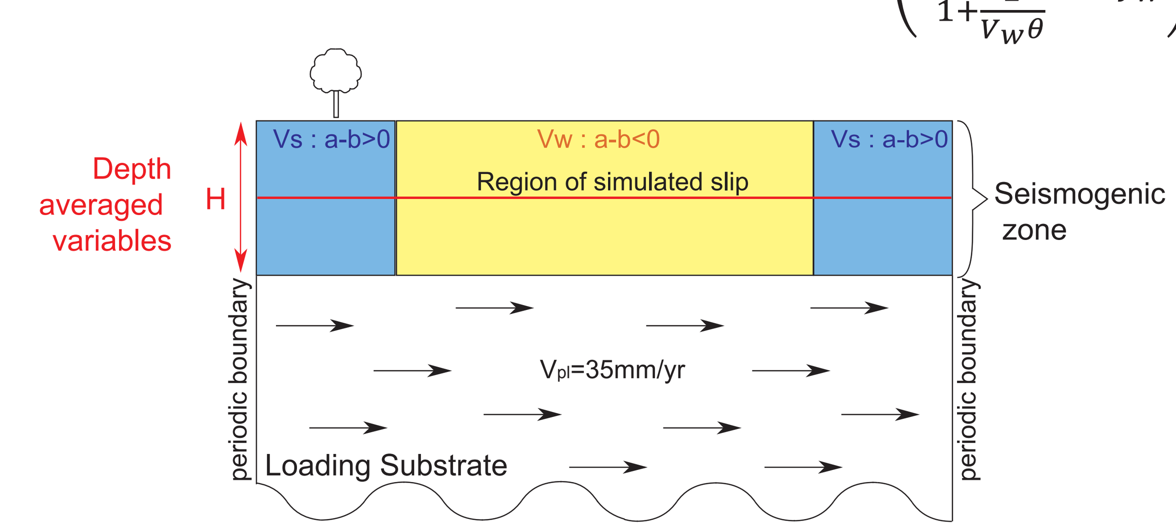
Figure (b): Slip velocity
- All events nucleate in the middle part in the weaker patch in FD model, and mostly on the boundary between the VS and VW zones in the QD model.
- All events propagate to the end of the velocity-weakening region in FD model.
- Events are more "pulse-like" in FD model, and more "crack-like" in QD model.

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

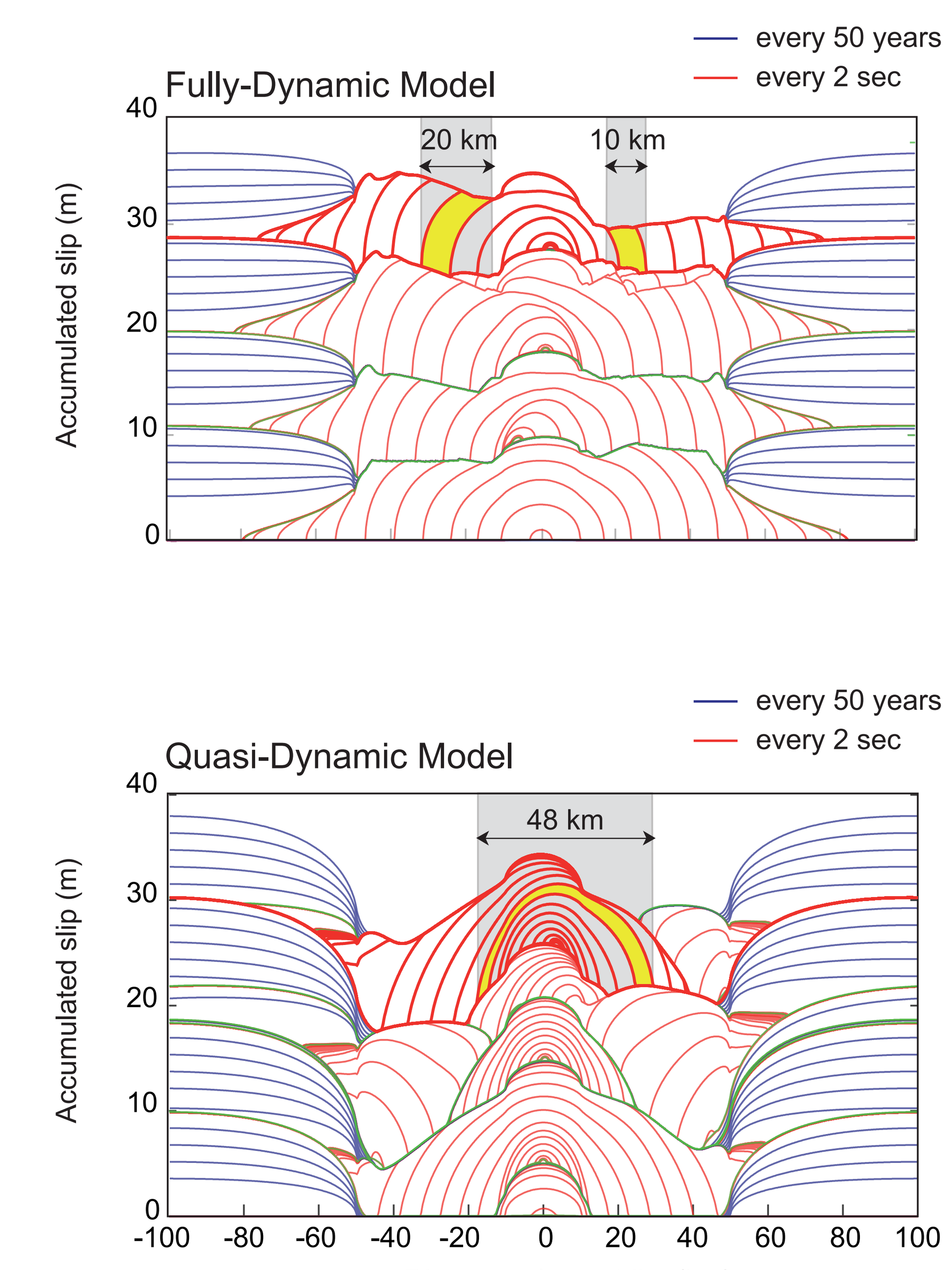
Figure (d) : Maximun sliding velocity
- Average shear stress is higher in QD model than in FD model.

(a) Model

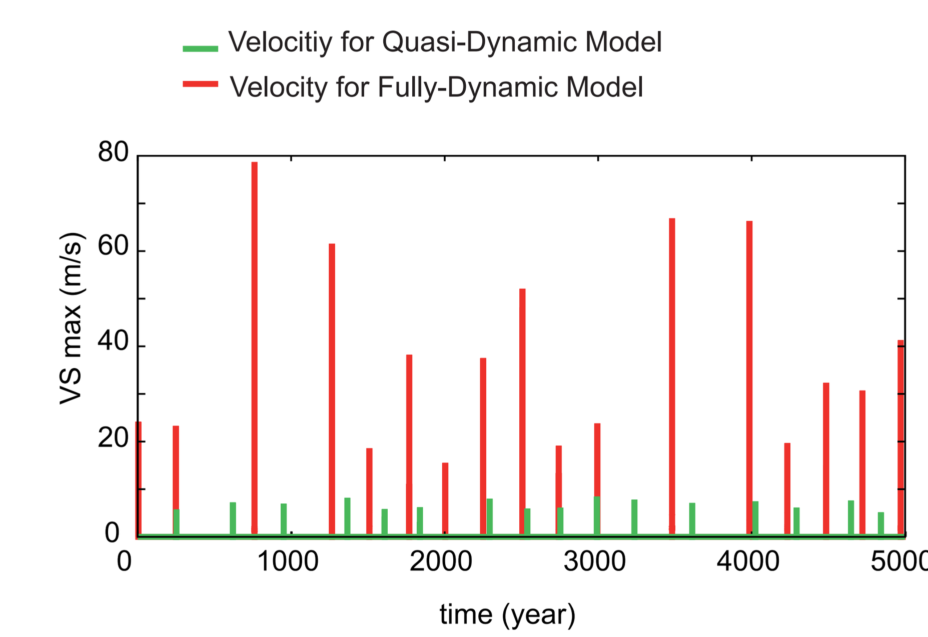
friction law: $\tau = \bar{\sigma}\left(\frac{f_{R\&S} - f_w}{1 + \frac{L}{V_w\theta}} + f_w\right)$



(b) Slip history



(c) Maximum Sliding Velocity



(d) Stress Drop