A Frictional-viscous-mixing Fault Model and Its implications for a Single Slow Slip Event Rupture

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(REF: Baoning Wu's PhD dissertation)

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Abstract

● It is well-known that the first-order kinematic source characteristics of typical earthquakes, such as slip rate, rupture propagation speed, and moment duration scaling, can be well-explained by a model where the fault experiences a sudden frictional strength drop.

● Slow slip events (SSEs) are slip transients similar to typical earthquakes, but their first-order source characteristics are quite different. For example, an SSE has a lower slip rate than a typical earthquake (fast earthquake). A sudden frictional strength drop model cannot explain SSEs to first order.

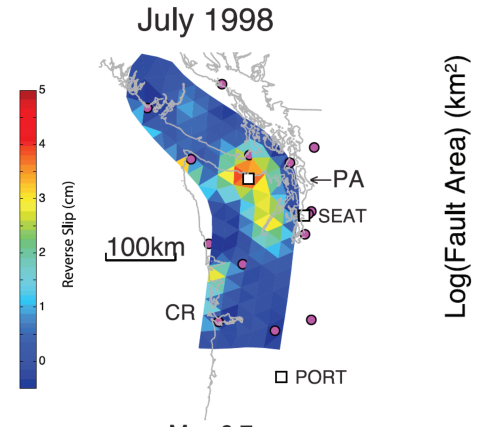
● We consider a frictional-viscous model (e.g., Ando et al., 2010) to explain the first-order characteristics of SSEs. It is inspired by the recent geological observations that imply the occurrence of SSEs in fault zones with a finite thickness of ~100s of meters. The bulk matrix of the fault zone deforms viscously, while pervasive frictional surfaces are distributed in the viscous matrix.

● Our frictional-viscous model can simultaneously explain various kinematic source parameters for SSEs, with the viscous coefficient η_v ≈ 10^4 - 10^5 μ/(2β) and stress drop ≈ ~10 kPa.

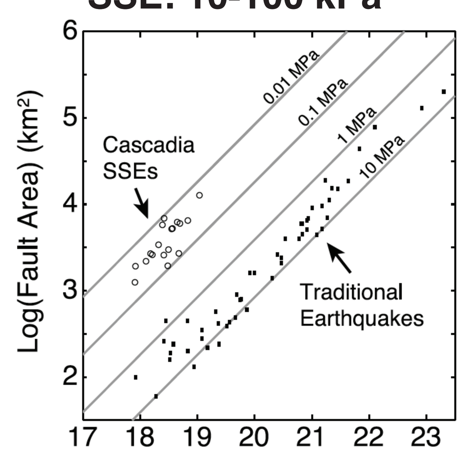
SSEs vs Fast EQs: 1st order observations

Static stress drop Δτ

Fast EQ: 1-10 MPa
SSE: 10-100 kPa

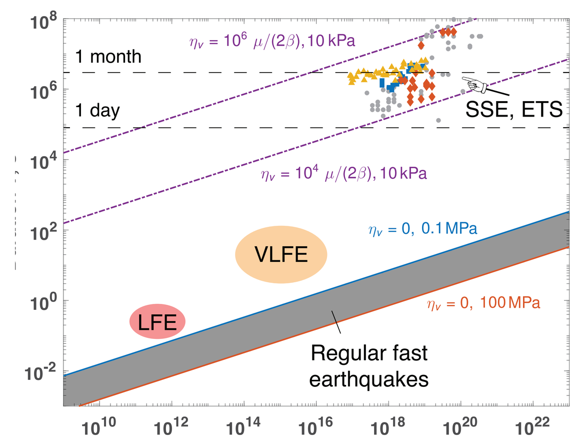


1998 M6.7 Cascadia SSE, Schmidt & Gao, 2010



SSEs vs Fast EQs, Schmidt & Gao, 2010

M0-T scaling

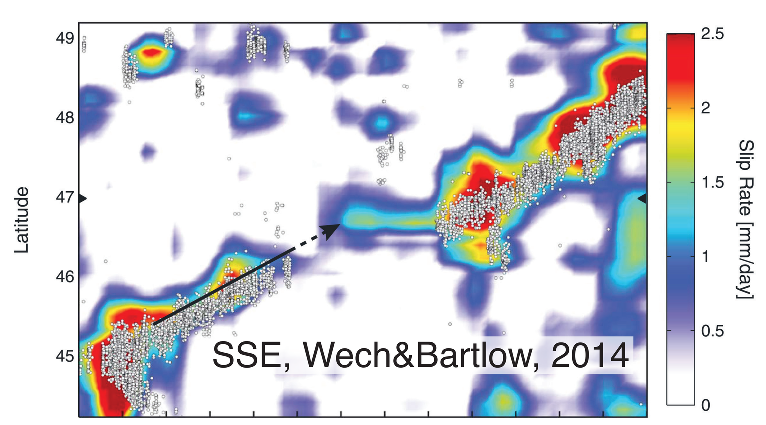


(SSE Data: Gao & Schmidt, 2010; Liu, 2014; Michel et al., 2019)

T of SSE is ~ 10^6 greater

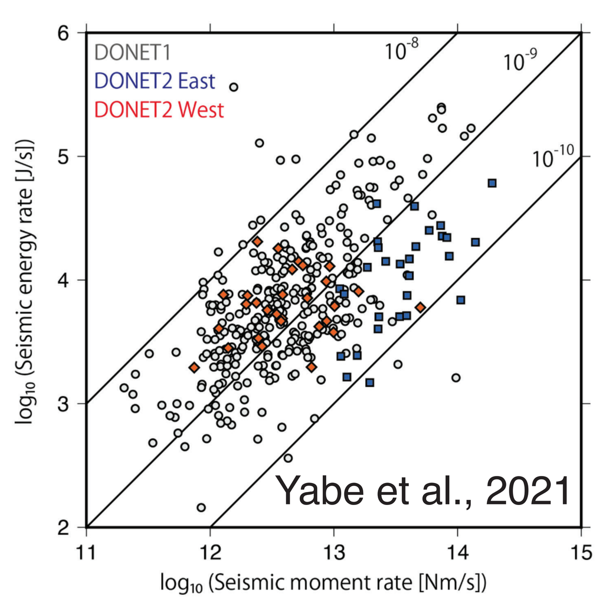
Slip rate V

Fast EQ: 0.1-1 m/s
SSE: 10^-8 - 10^-7 m/s



Energy/Moment

Fast EQ: 10^-6 - 10^-4
SSE: 10^-10 - 10^-8

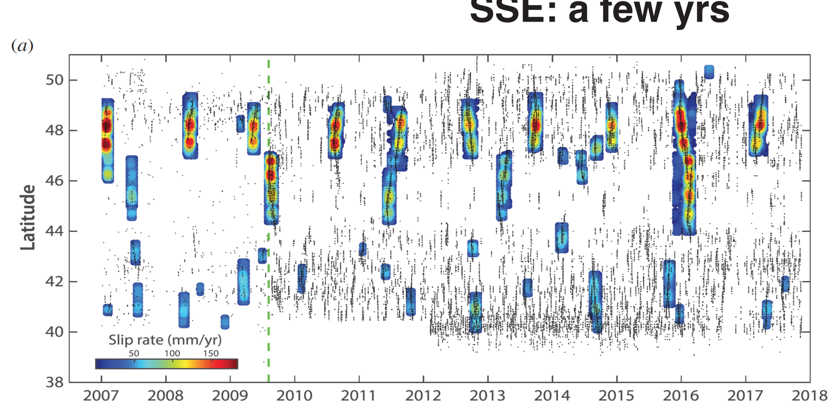


Rupture propagation speed Vr

Fast EQ: ~10^3 m/s
SSE: 0.1 - m/s

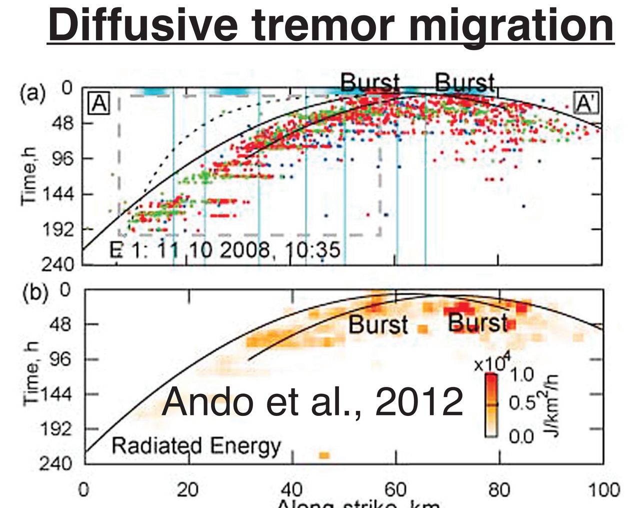
Inter-events interval

Fast EQ: ~100s yrs
SSE: a few yrs



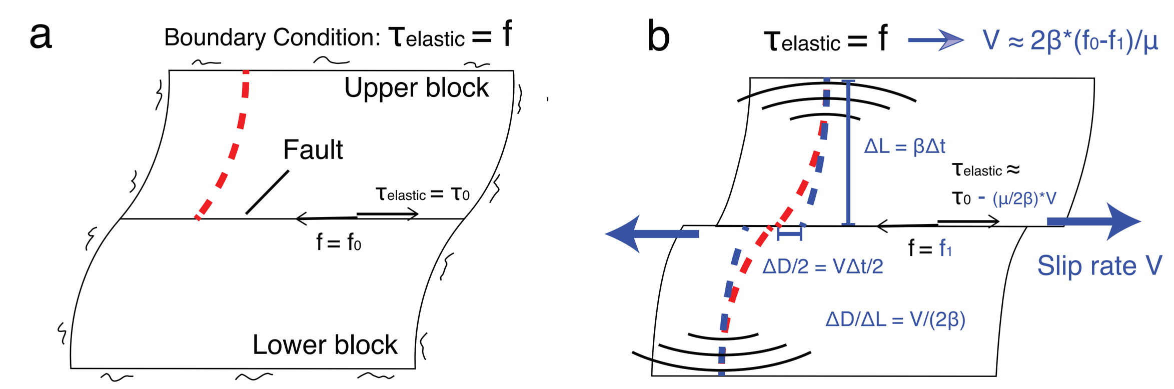
Behr & Bürgmann, 2021; Michel et al., 2019

Diffusive tremor migration



only SSEs have: Df ~ 10^3 m^2/s

A frictional-only sudden stress drop model

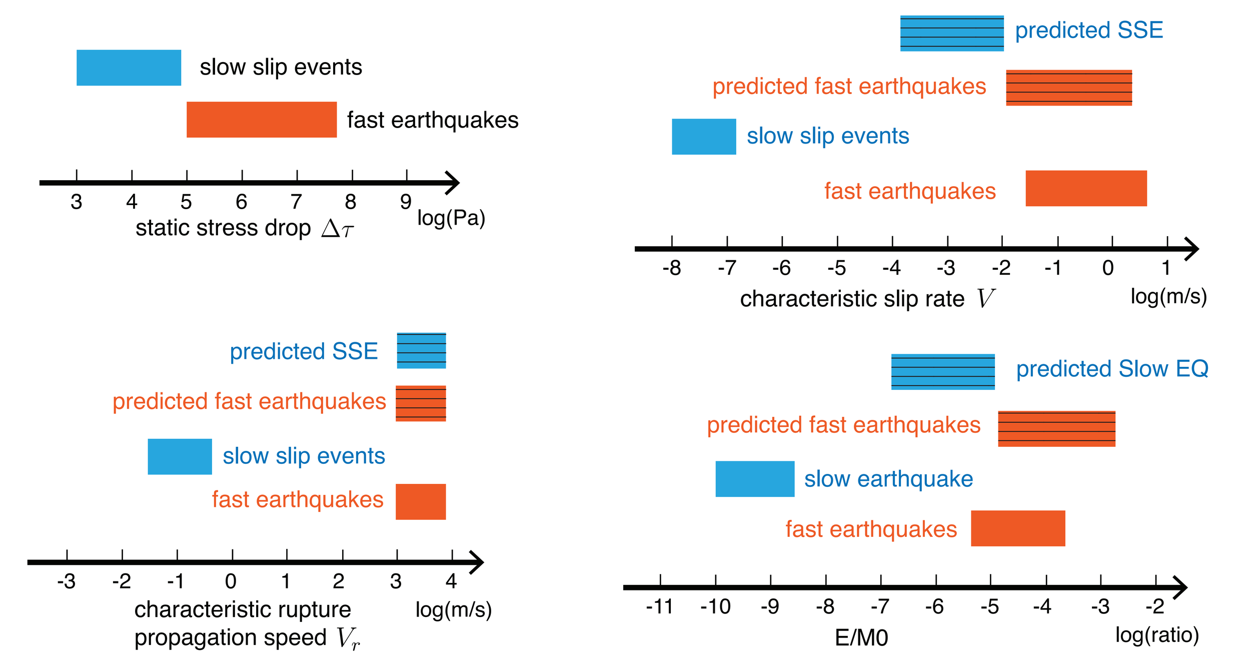


Theoretical relations (1st order) for the sudden stress drop model:

$$\Delta\tau \approx \mu\frac{D}{L} \qquad V_r \approx \beta \qquad \frac{E}{M_0} \approx \frac{\Delta\tau}{2\mu}$$

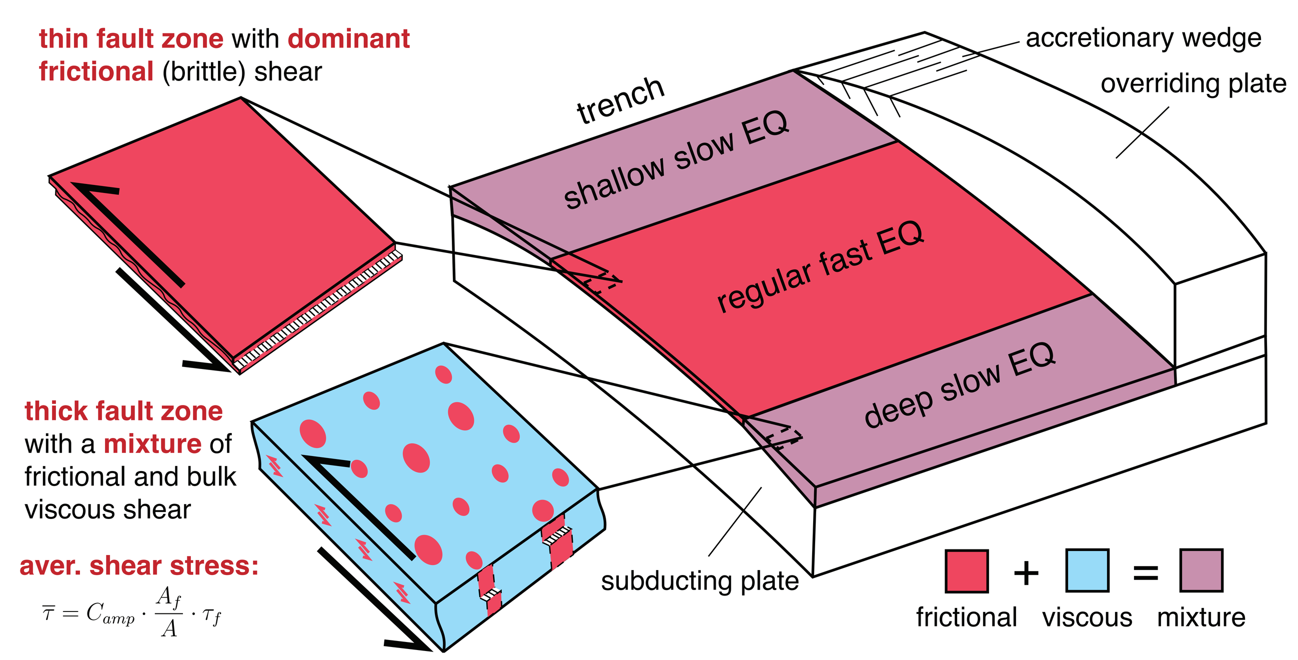
$$V \approx \frac{2\Delta\tau}{\mu}\cdot\beta \qquad M_0 \approx \Delta\tau\cdot\beta^3\cdot T^3$$

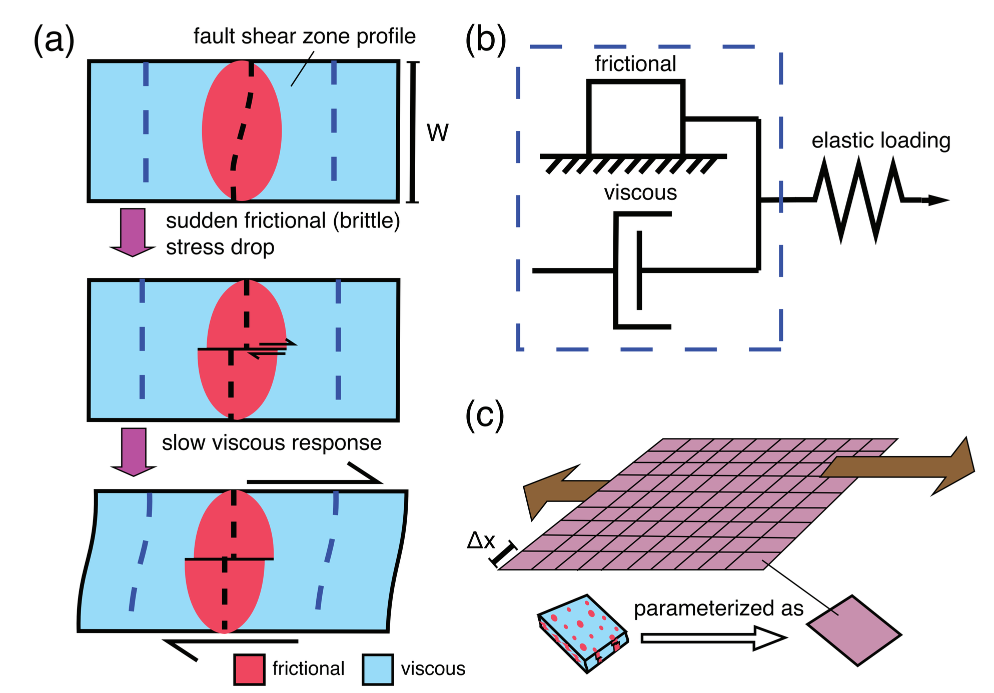
(e.g., Kanamori 1977; Aki & Richards, 2002)



● **Sudden stress drop model can explain fast EQs to first order. But it cannot explain SSE**

A frictional-viscous in parallel model: setup





● The physical picture of the present model: fast EQs happen on frictional-only faults. SSEs happen on frictional-viscous mixing faults, where the 3D fault zone mostly consists of viscous deformation, while frictional (brittle) deformation sparsely exists in the fault zone as well.

● These 3D features are parameterized as "friction law" on a 2D fault. The total fault strength equals the sum of the frictional and viscous strength components. The frictional strength can experience a sudden drop (slip-weakening), while the viscous strength increases linearly with slip rate V. Such a boundary condition is equivalent to a mechanical system where the frictional and viscous force act in parallel. (e.g., Ando et al., 2010; Lavier et al., 2013; Beall et al.,2019).

Effective friction law:

When $\tau_{elastic} < f_0$ **, fault stays locked, and V=0;**

Once $\tau_{elastic} \geq f_0$ **, fault starts to slip, and we have**

$$\tau_{elastic} = f_0 - (f_0 - f_1)\cdot\frac{D}{D_0} + \eta_v\cdot V, \text{ when } D \leq D_0$$

$$\tau_{elastic} = f_1 + \eta_v\cdot V, \text{ when } D > D_0$$

Two KEY "friction law" parameters:

$\Delta\tau$ **: frictional strength drop** η_v **: viscous coefficient**

A frictional-viscous in parallel model: analytical relations

$$\Delta\tau \approx \mu\frac{D}{L}, \quad V_r \approx \left(1+\frac{1}{S}\right)\cdot\left(1+\frac{\eta_v}{\mu/(2\beta)}\right)^{-1}\cdot 2\beta,$$

$$V \approx \left(1+\frac{\eta_v}{\mu/(2\beta)}\right)^{-1}\cdot\frac{2\Delta\tau}{\mu}\cdot\beta, \quad M_0 \approx \Delta\tau\cdot\left(1+\frac{\eta_v}{\mu/2\beta}\right)^{-3}\cdot\beta^3\cdot T^3,$$

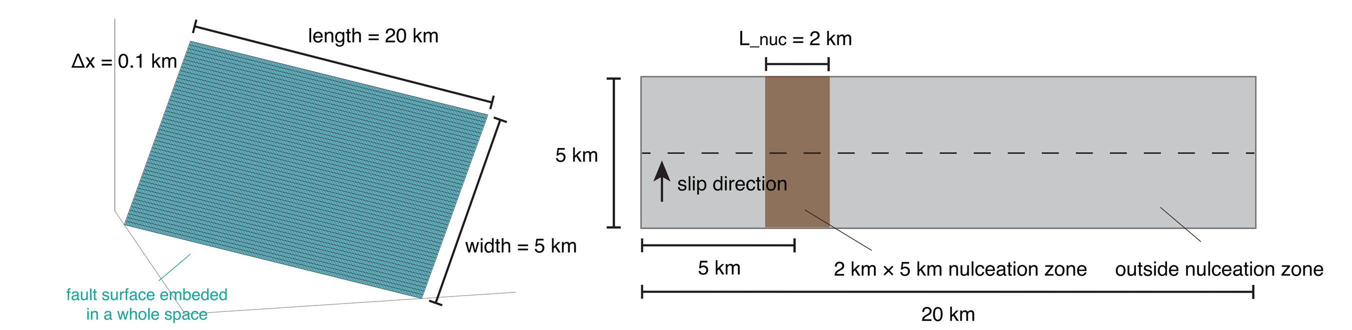
$$\frac{E}{M_0} \approx \frac{\Delta\tau}{2\mu}\cdot\left(1+\frac{\eta_v}{\mu/(2\beta)}\right)^{-1}, \quad D_f \approx C\cdot\frac{\Delta\tau}{\tau_e}\cdot\left(1+\frac{\eta_v}{\mu/(2\beta)}\right)^{-1}\cdot L\cdot 2\beta$$

(Please ask Baoning for details!)

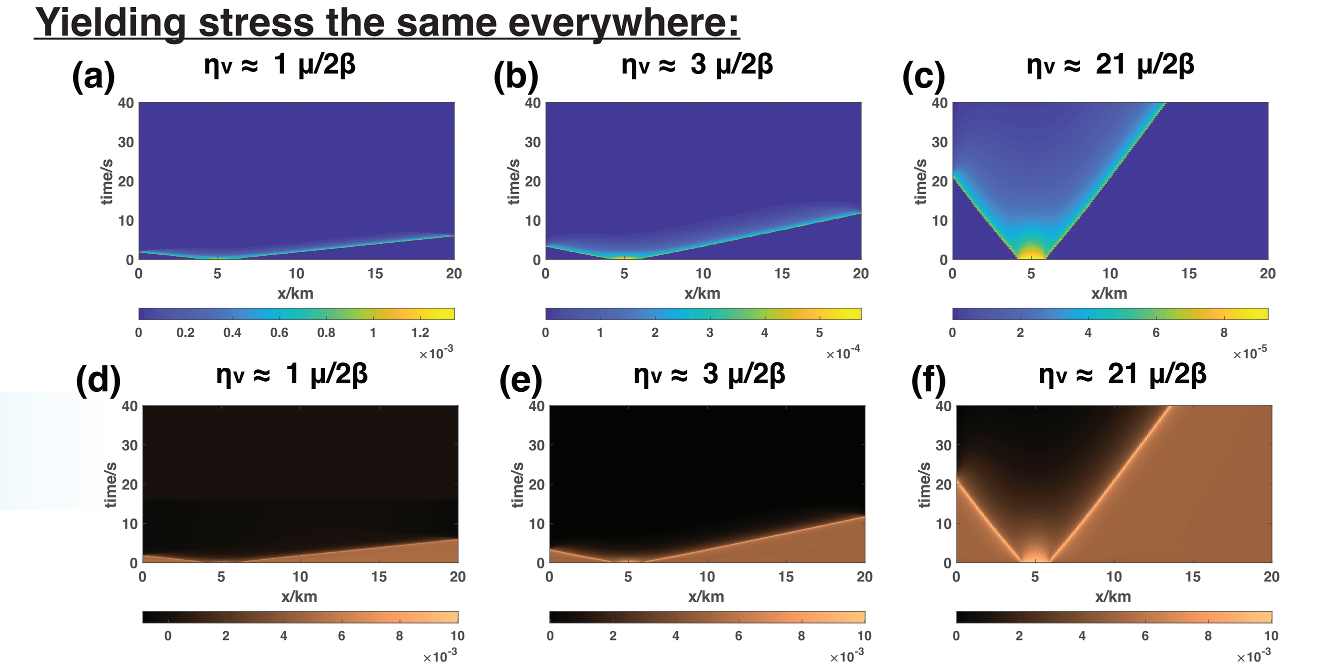
- η_v affects the source kinematics through $\left(1+\frac{\eta_v}{\mu/(2\beta)}\right)^{-1}$
- As η_v increases --> V and Vr decreases, T increases
- M0-T scaling remains $M_0 \propto T^3$
- When $\eta_v \approx 10^4 - 10^5\ \mu/(2\beta)$ & $\Delta\tau \approx 10$ kPa, all these kinematic parameters are simultaneously explained with the frictional-viscous model.

Numerical validations of analytical results

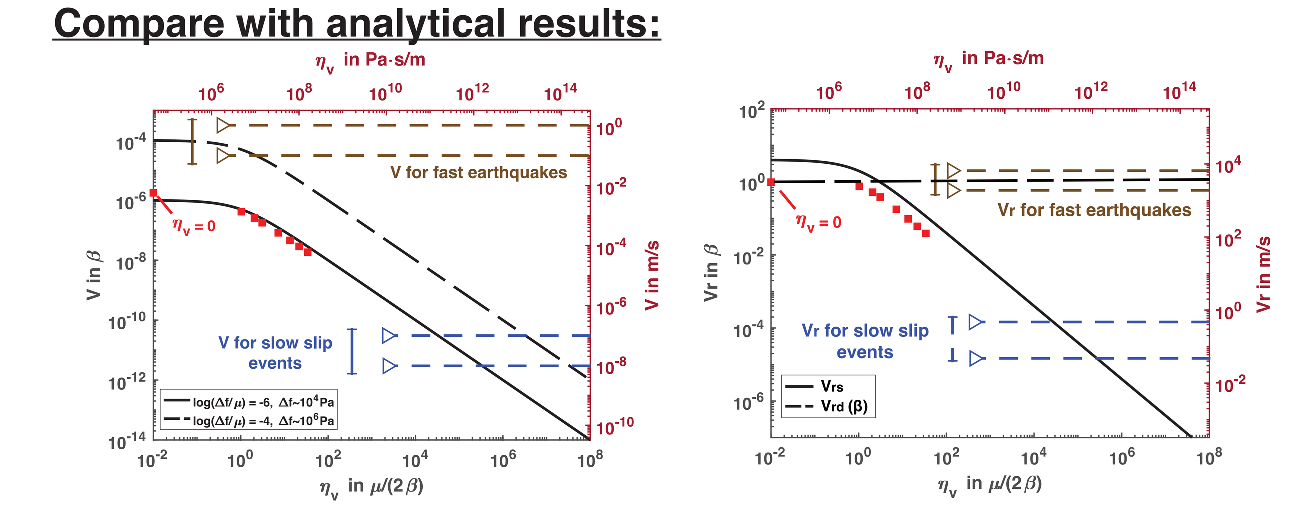
3D BIEM dynamic rupture simulations:



Yielding stress the same everywhere:

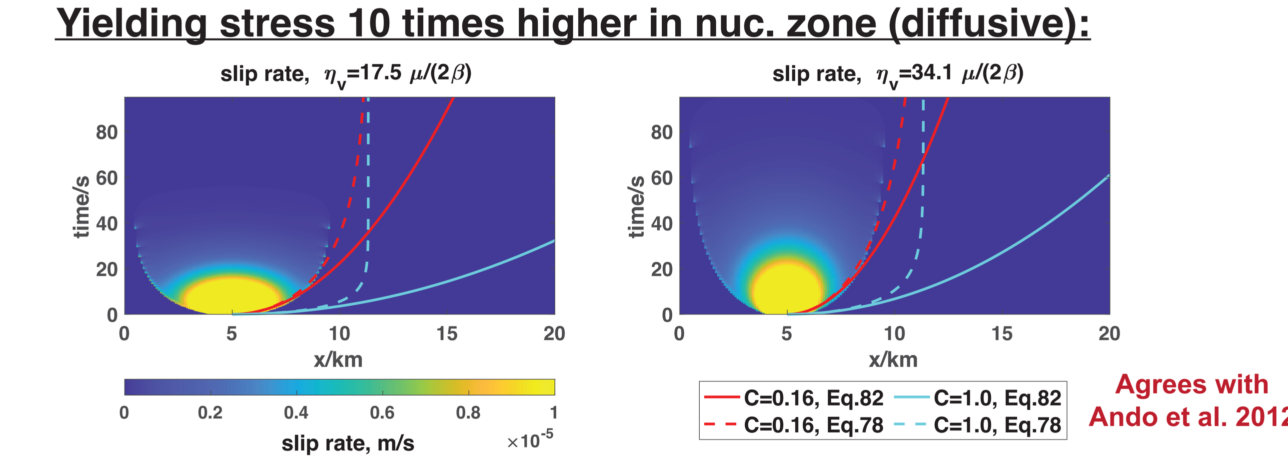


Compare with analytical results:

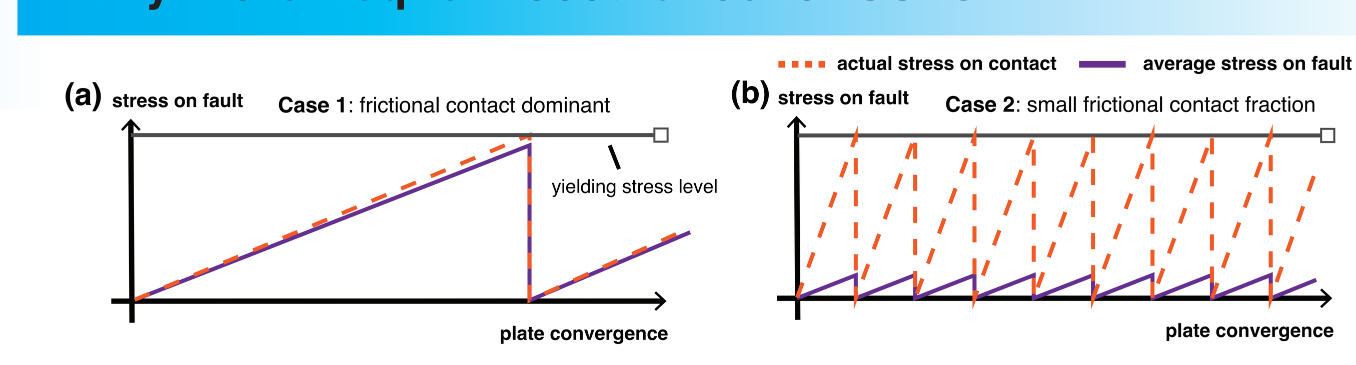


● **Explicit stress/friction heterogeneity is not required to generate slow slip rate V and slow rupture propagation speed Vr.**

Yielding stress 10 times higher in nuc. zone (diffusive):



Why more frequent occurance for SSEs?



● **Stress concentration/amplification effect** for the frictional-viscous model: the actual shear stress on the frictional contact builds up significantly faster than the average shear stress on the fault, because of the small fraction of the area that is frictionally locked needs to bear the load for a considerably greater area. As a result, a frictional-viscous fault would have a **shorter event interval** and a **smaller average stress drop.**