From Single-event Dynamics to Multi-cycle Dynamics of Geometrically Complex Faults

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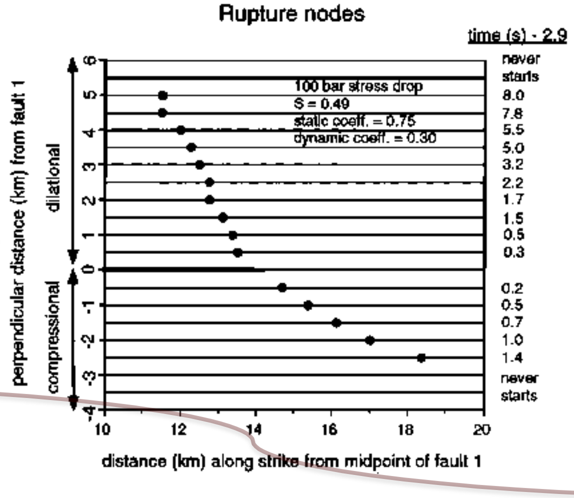
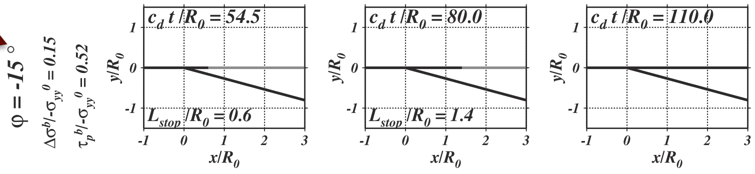
Outline

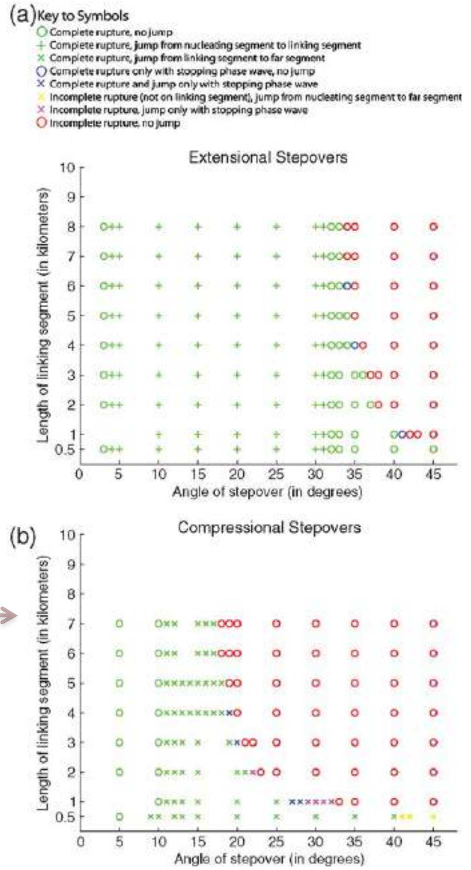
- Review of single-event dynamics of complex faults
- Motivations to multi-cycle dynamics
- A 2D multi-cycle model &its application to a real fault system
- Efforts to develop 3D multi-cycle dynamic methods for geometrically complex faults
  - **EQdyna + Dynamic relaxation (FEM): Bin Luo**
  - **EQdyna + EQquasi (FEM): Dunyu Liu**

Review of single-event dynamics

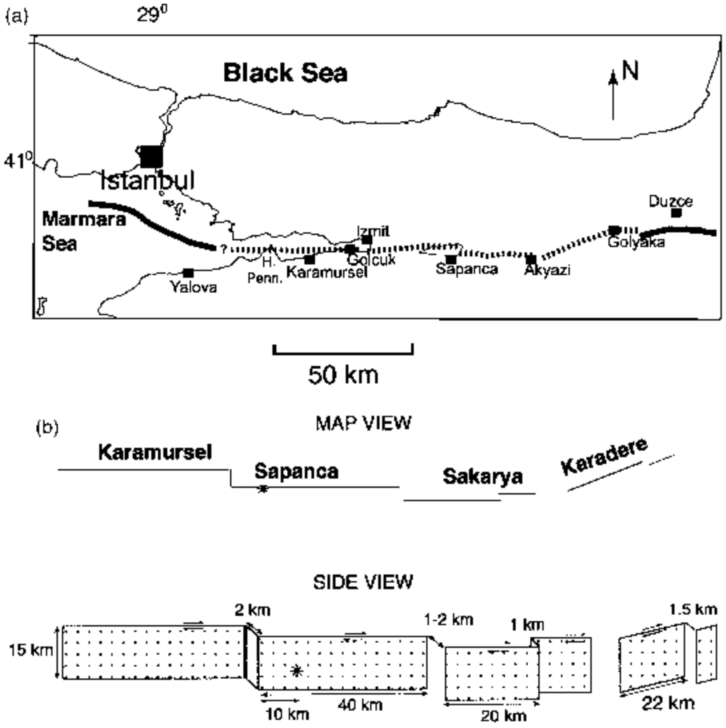
- Classical 2D models
  - Stepover: e.g., Harris and Day (1993), Lozos et al. (2011) …
  - Branch: e.g., Kame et al. (2003) …
  - Bend



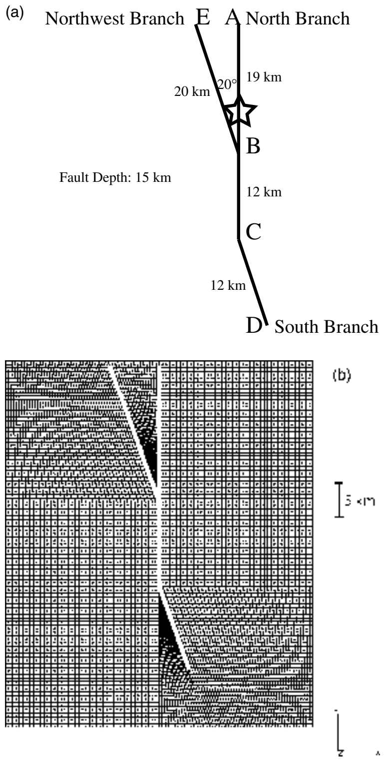




- Some 3D models: e.g., Harris et al. (2002), Oglesby et al. (2003)



Heterogeneous initial stress is needed to reproduce actual ruptures!

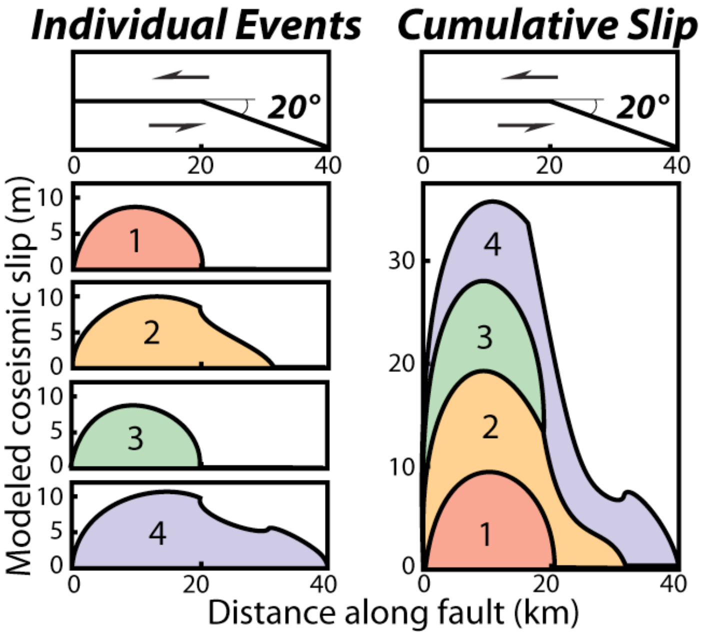


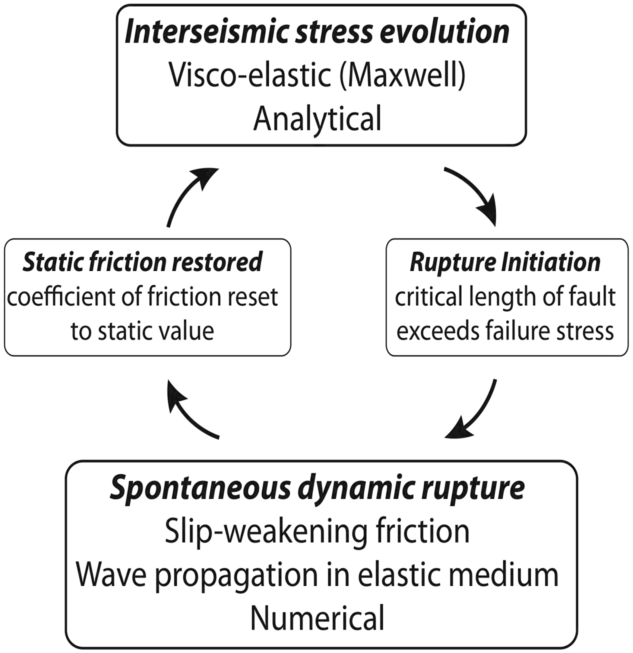
Motivations for Multi-Cycle Dynamics of Complex Faults

- **Need of initial stress fields that are consistent** with fault geometry and faulting history for dynamic rupture models
- **Earthquake simulators on realistically complex faults with fully dynamics included**
- **Assimilate big data of observations** associated with earthquakes, including coseismic, postseismic, interseismic (&nucleation?)

A 2D Multi-cycle Dynamic Model of Complex faults

- Duan and Oglesby (2005, 2006, 2007)





Interseismic stress evolution
Visco-elastic (Maxwell)
Analytical

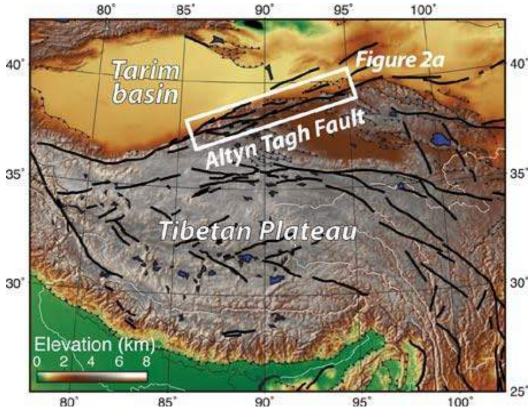
Rupture Initiation
critical length of fault exceeds failure stress

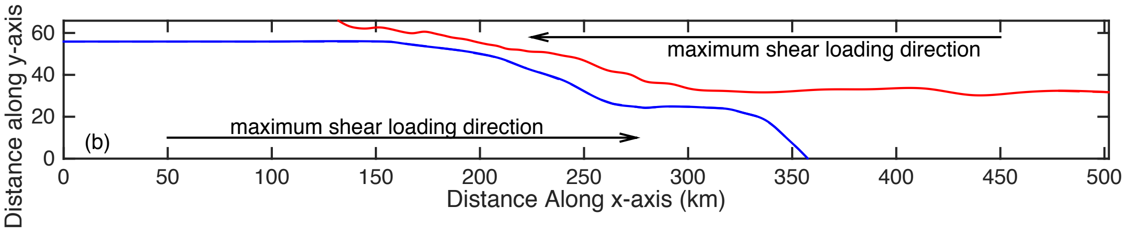
Spontaneous dynamic rupture
Slip-weakening friction
Wave propagation in elastic medium
Numerical

Static friction restored
coefficient of friction reset to static value

A 2D Model of the Aksay Bend along the Altyn Tagh Fault

- Fault geometry
- Preliminary results





Duan et al. (2018), to be submitted.

Developing 3D Multi-Cycle Dynamic Methods

- **Extensions** of our dynamic FEM code **EQdyna**:
  - Implement rate- & state- friction laws of various forms: **Bin Luo**
  - Implement PML and coarse-grain Q modeling: **Dunyu Liu**
- **New developments**:
  - **Adaptive dynamic relaxation (DR)** for quasi-static processes of earthquake cycles with dynamic code EQdyna: **Bin Luo**
  - Develop **quasi-static FEM solver** and integrate with EQdyna: **Dunyu Liu**

Study I: Spontaneous Dynamic Rupture Simulation on Geometrically Complex Faults Governed by Different Friction Laws

Bin Luo and Benchun Duan, 2018, in revision

Various Friction Laws

- Slip-weakening

$$\mu = \mu_s + (\mu_s - \mu_d)\min\left(\frac{\delta}{d_0}, 1\right),$$

- RSF Aging law

$$\mu = a\,\mathrm{arcsinh}\left[\frac{V}{2V_0}\exp\left(\frac{f_0 + b\ln\frac{V_0\theta}{L}}{a}\right)\right], \qquad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L},$$

- RSF Slip law

$$\mu = a\,\mathrm{arcsinh}\left[\frac{V}{2V_0}\exp\left(\frac{\Psi}{a}\right)\right], \qquad \frac{d\Psi}{dt} = -\frac{V}{L}(\Psi - \Psi_{ss}),$$

$$\Psi_{ss} = a\ln\left[\frac{2V_0}{V}\sinh\left(\frac{f_{ss}}{a}\right)\right],$$

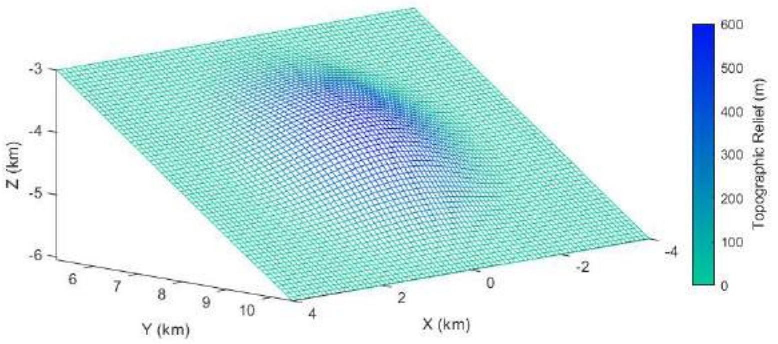
$$f_{ss} = f_0 - (b - a)\ln\frac{V}{V_0},$$

- RSF Flash Heating

$$f_{ss} = f_w + \frac{f_{LV} - f_w}{\left[1 + \left(\frac{V}{V_w}\right)^8\right]^{1/8}},$$

Large-scale Geometrical Complexity

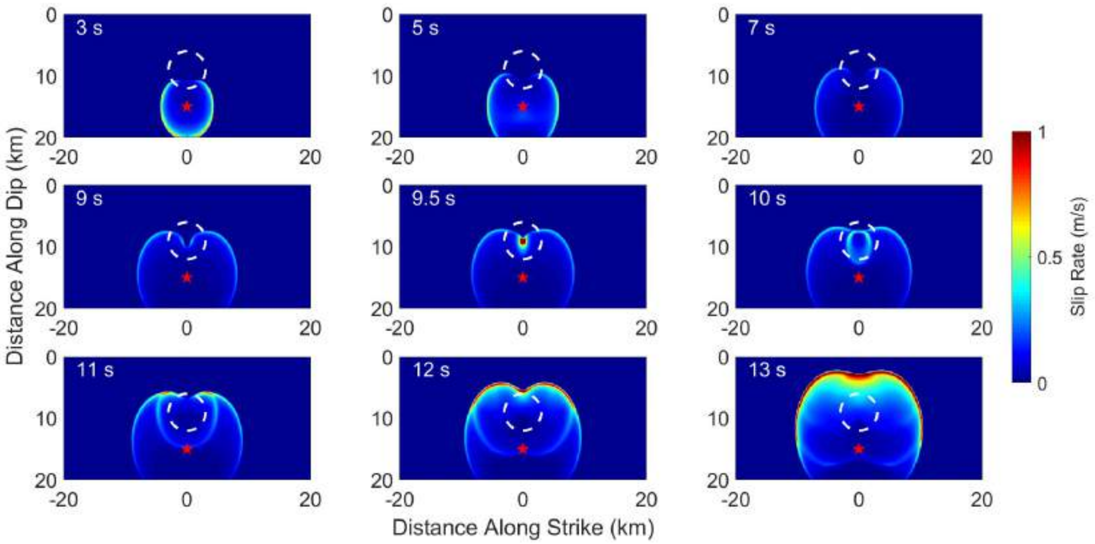
We use the 3-D finite element code EQdyna to perform a series of dynamic rupture simulations governed by various friction laws on a three-dimensional subduction fault model with local non-planar bumpy geometry.



Rupture Behavior

Rupture Type Classification

Height (m)	SW	RS-A	RS-S	RS-FH
300	A	A	A	A
600	C	B	B	B
900	C	C	B	B

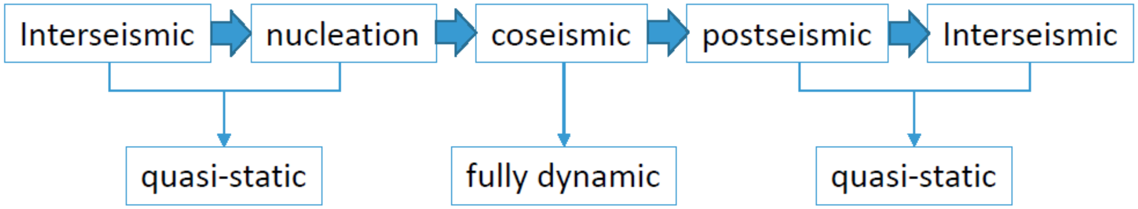


Study II: Three-dimensional Earthquake Cycle Simulation on Rate- and State-dependent Dip-slip Faults

Bin Luo and Benchun Duan, 2018, **In Preparation**

Earthquake Cycle

- An ideal earthquake cycle simulation attempts to reproduce a series of different faulting behavior: interseismic, nucleation, coseismic and postseismic.
- The coseismic period: dynamic rupture process
- The interseismic, nucleation and postseismic periods: slow tectonic loading processes assumed to be quasi-static.

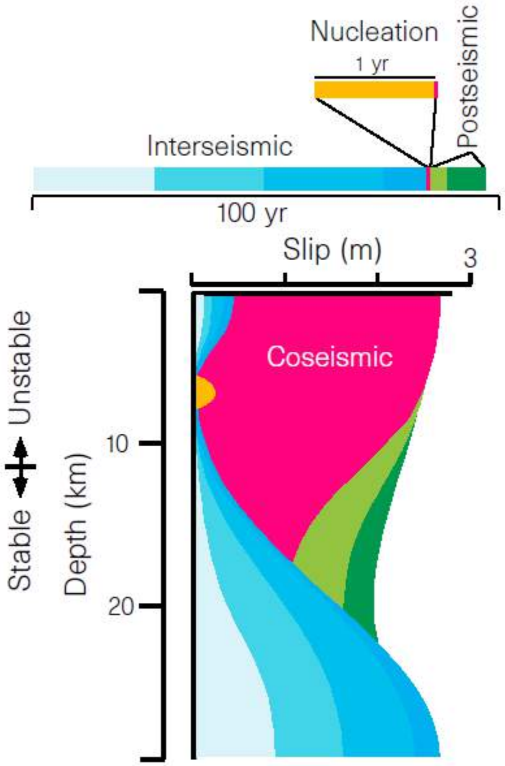


Interseismic → nucleation → coseismic → postseismic → Interseismic

quasi-static

fully dynamic

quasi-static



Scholz, 1998

Adaptive Dynamic Relaxation

- The main idea of dynamic relaxation is that the long-term limit of a damped dynamic solution reaches the quasi-static solution of given initial and boundary conditions.
- DR introduces a mass damping factor α to the FEM matrix form of the equations of motion in continuum mechanics:

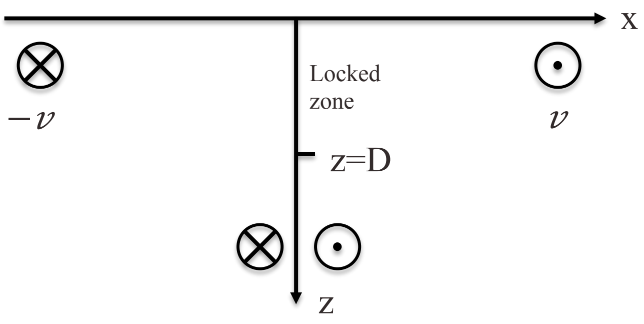
$$\mathbf{M}a_t + \alpha\mathbf{M}v_t + \mathbf{K}\vec{u}_t = F_t$$

- The best choice of α is:

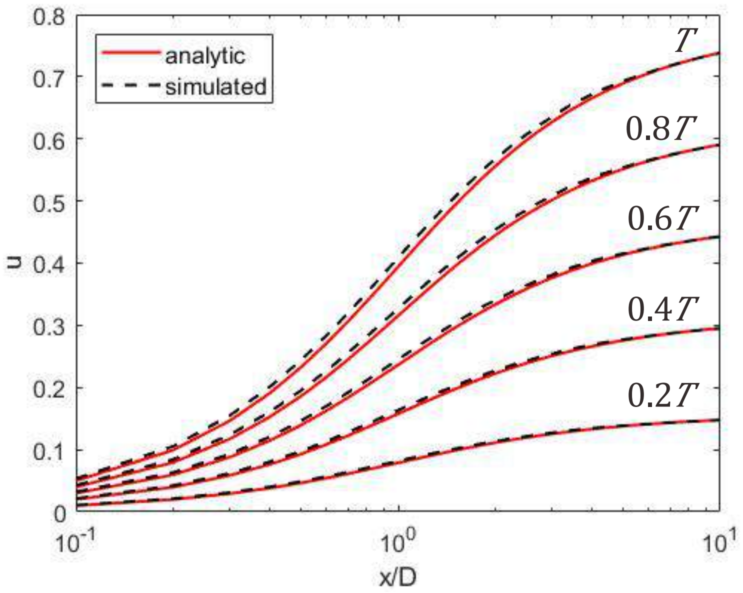
$$\alpha_{opt} = 2\sqrt{\frac{\lambda_{min}\lambda_{max}}{\lambda_{min} + \lambda_{max}}}$$

where λ_{min}, λ_{max} are minimum and maximum eigenvalues of matrix $\mathbf{M}^{-1}\mathbf{K}$.

Dynamic Relaxation Verification

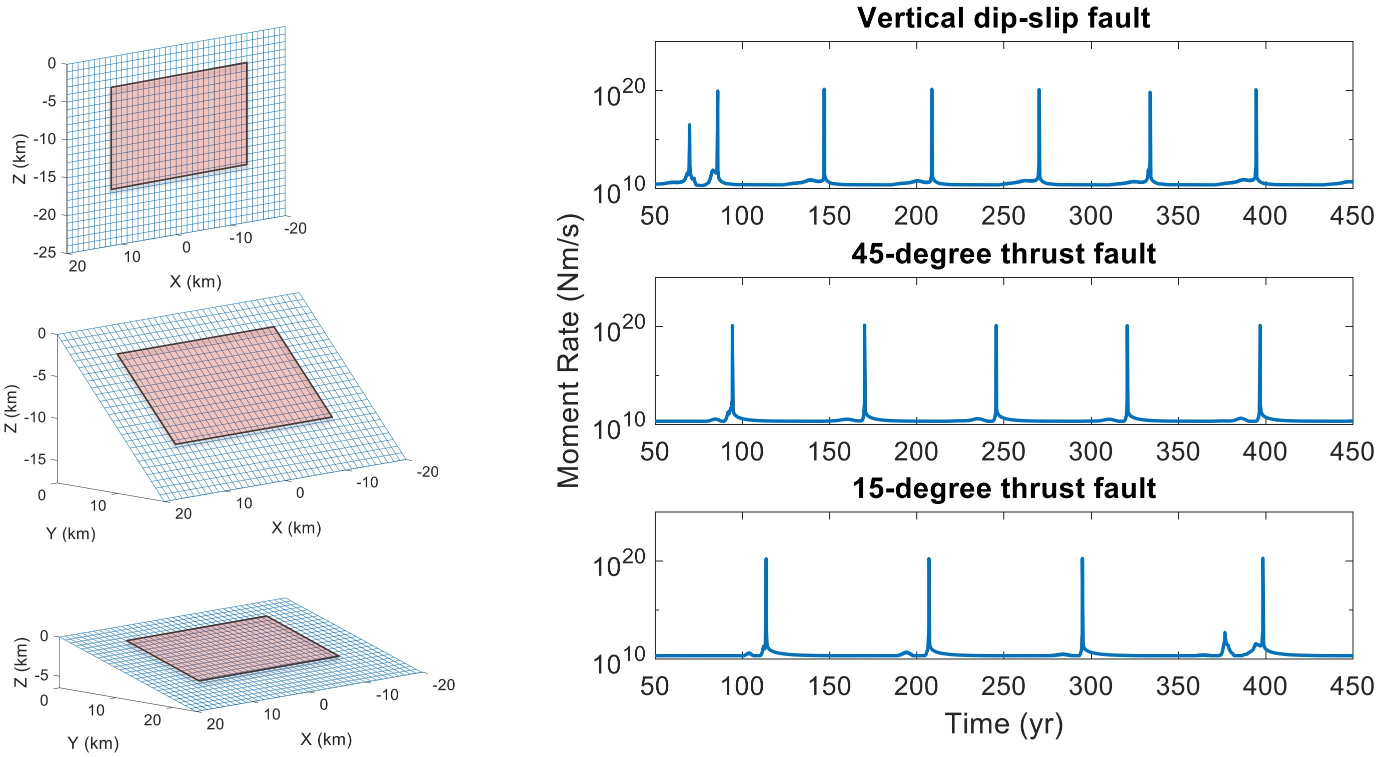


$$\frac{u(x,0,t)}{2vt} = \pm\frac{n}{2} + \frac{t-nT}{\pi T}\tan^{-1}\frac{x}{D}$$



Savage and Prescott, 1978

Moment Rate Function

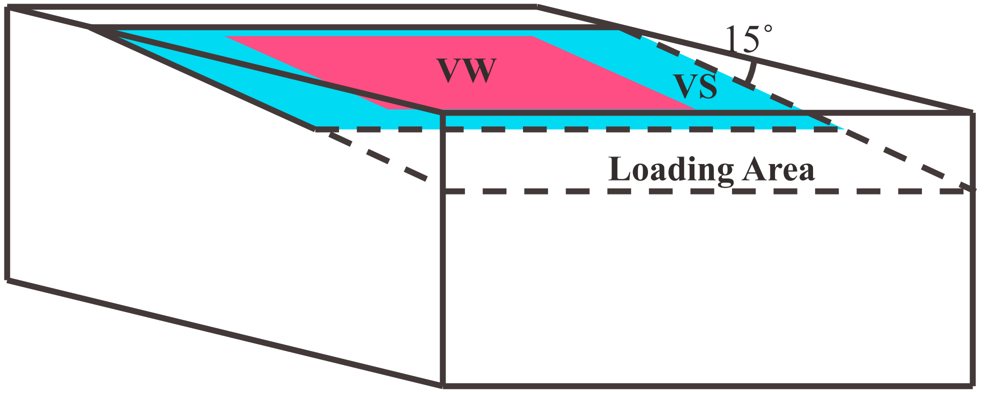


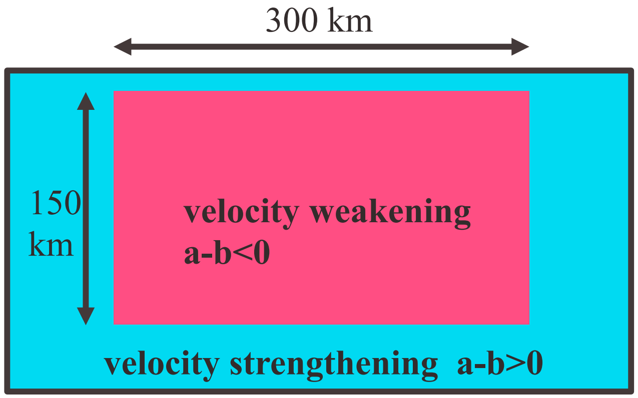
Comparison of moment rate functions of earthquake sequences on thrust faults with different dipping angles.

Study III: Three-dimensional Earthquake Cycle Simulation on a Rate- and State-dependent **Non-planar Subduction Plane**

Bin Luo and Benchun Duan, 2018, **In Preparation**

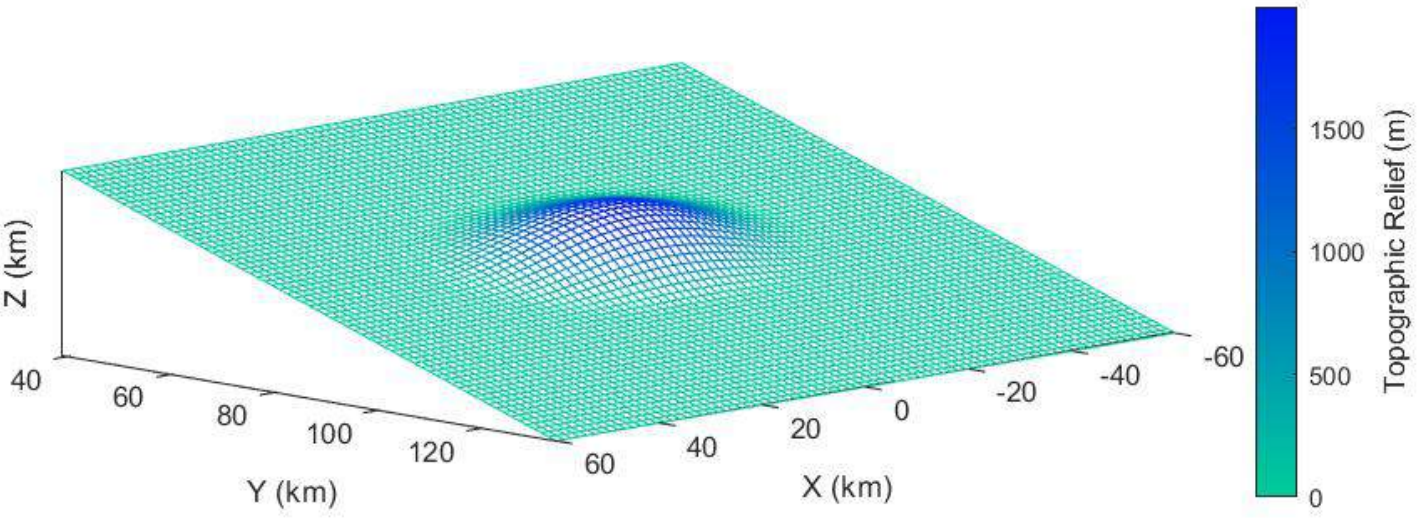
Subduction Fault Model



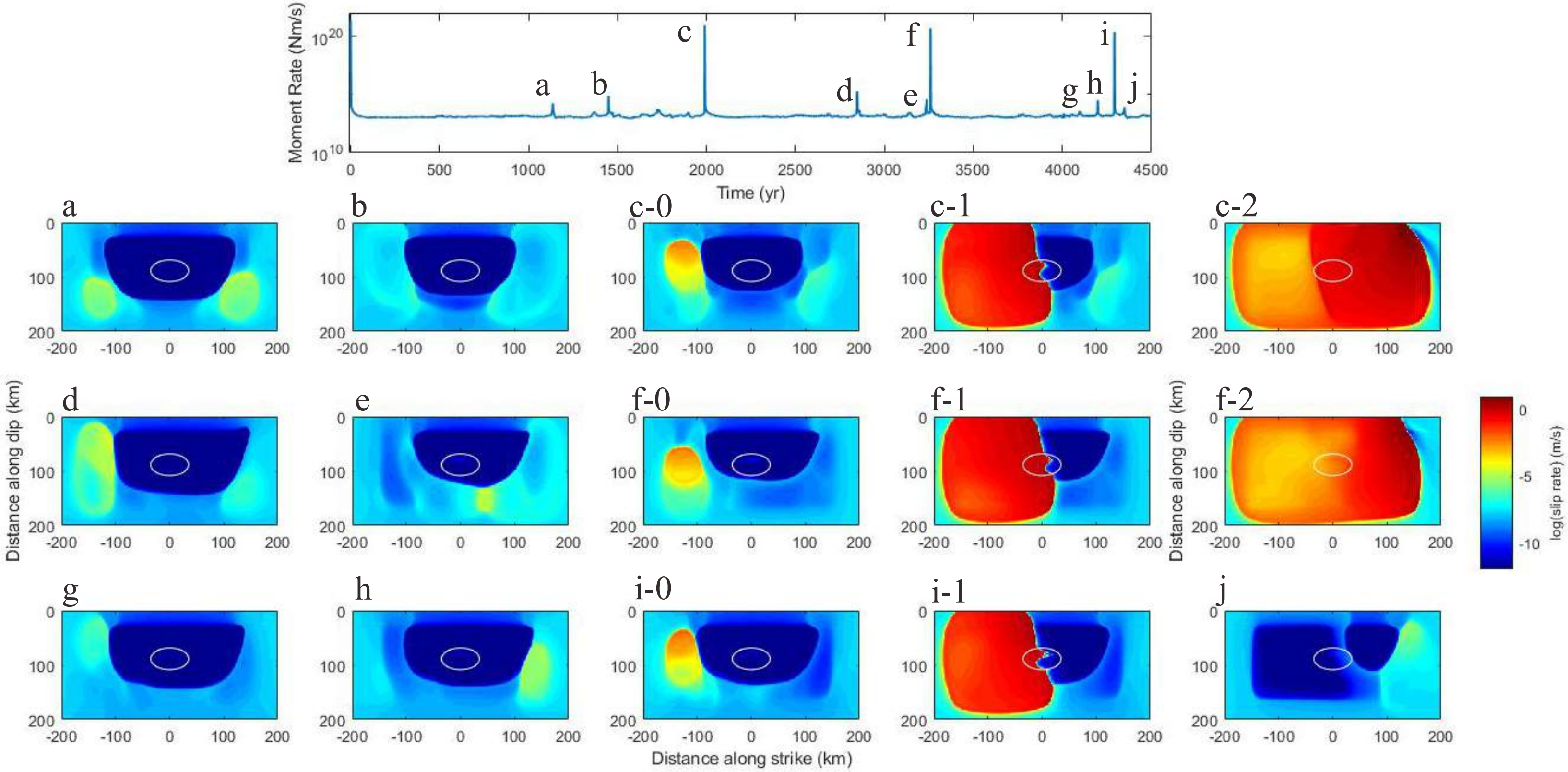


- A thrust fault is embedded in a finite element model
- The dynamic model uses PML to absorb seismic waves
- The quasi-static model uses boundaries with assigned loading velocity

Non-planar Fault Geometry

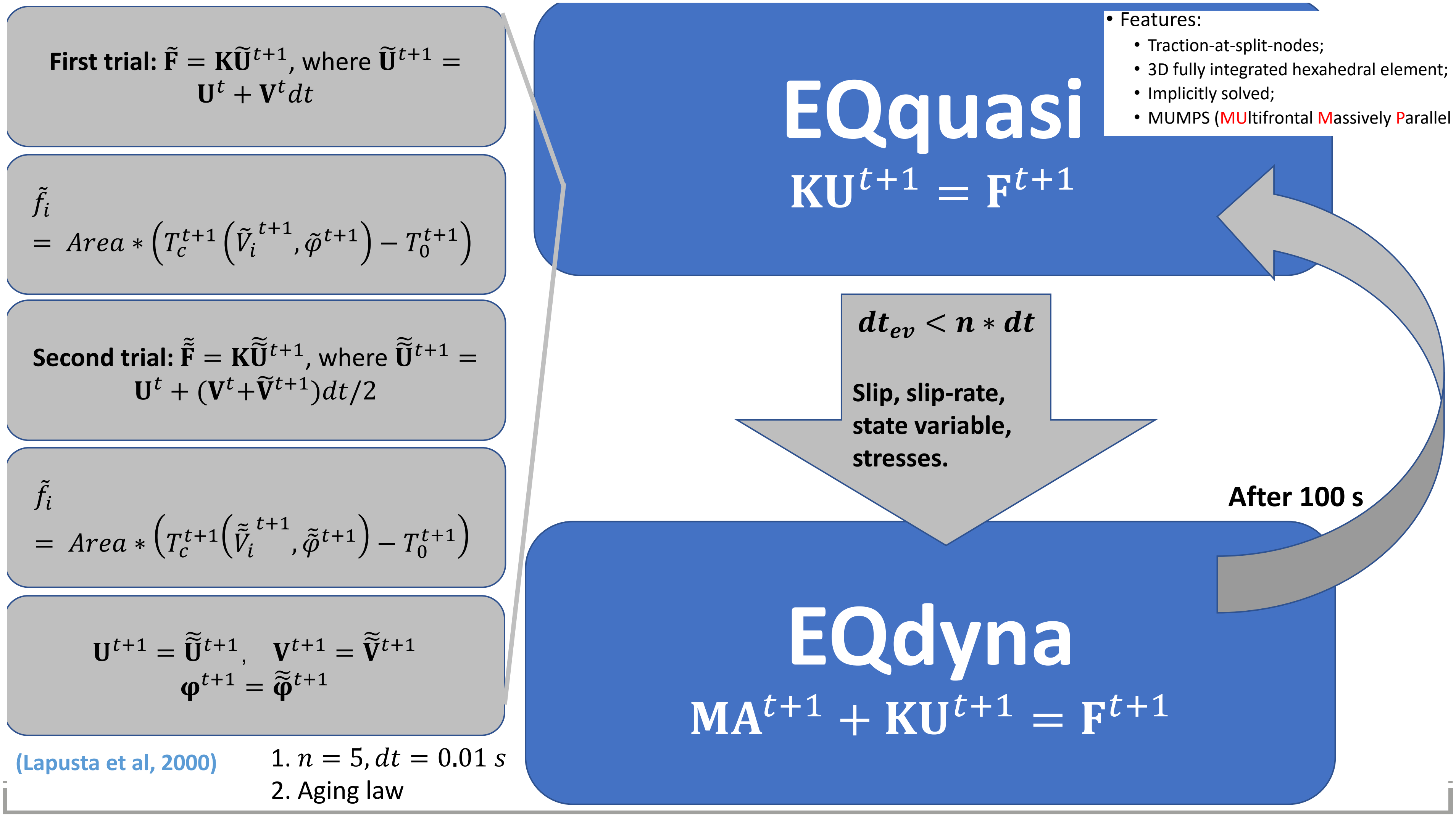


Earthquake Sequence on Non-planar Fault



Study IV: A 3D Multicycle Method Integrating Quasi-static FEM and EQdyna for Complex Faults

Dunyu Liu and Benchun Duan, 2018, **In Preparation**



First trial: $\tilde{\mathbf{F}} = \mathbf{K}\tilde{\mathbf{U}}^{t+1}$, where $\tilde{\mathbf{U}}^{t+1} = \mathbf{U}^t + \mathbf{V}^t dt$

$$\tilde{f}_i = Area * \left(T_c^{t+1}\left(\tilde{V}_i^{t+1}, \tilde{\varphi}^{t+1}\right) - T_0^{t+1}\right)$$

Second trial: $\tilde{\tilde{\mathbf{F}}} = \mathbf{K}\tilde{\tilde{\mathbf{U}}}^{t+1}$, where $\tilde{\tilde{\mathbf{U}}}^{t+1} = \mathbf{U}^t + (\mathbf{V}^t + \tilde{\mathbf{V}}^{t+1})dt/2$

$$\tilde{f}_i = Area * \left(T_c^{t+1}\left(\tilde{\tilde{V}}_i^{t+1}, \tilde{\tilde{\varphi}}^{t+1}\right) - T_0^{t+1}\right)$$

$$\mathbf{U}^{t+1} = \tilde{\tilde{\mathbf{U}}}^{t+1}, \quad \mathbf{V}^{t+1} = \tilde{\tilde{\mathbf{V}}}^{t+1}$$
$$\boldsymbol{\varphi}^{t+1} = \tilde{\tilde{\boldsymbol{\varphi}}}^{t+1}$$

(Lapusta et al, 2000)

1. $n = 5, dt = 0.01\ s$
2. Aging law

EQquasi

$$\mathbf{K}\mathbf{U}^{t+1} = \mathbf{F}^{t+1}$$

- Features:
  - Traction-at-split-nodes;
  - 3D fully integrated hexahedral element;
  - Implicitly solved;
  - MUMPS (MUltifrontal Massively Parallel

$$dt_{ev} < n * dt$$

Slip, slip-rate, state variable, stresses.

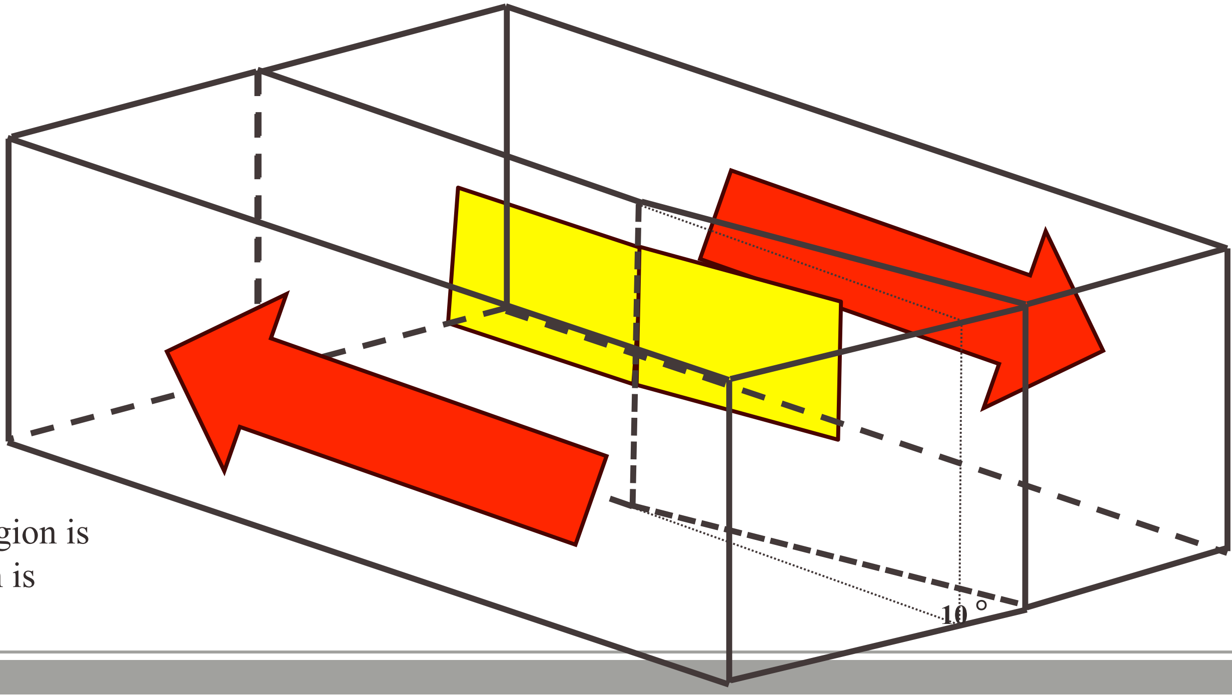
After 100 s

EQdyna

$$\mathbf{M}\mathbf{A}^{t+1} + \mathbf{K}\mathbf{U}^{t+1} = \mathbf{F}^{t+1}$$

Strike-slip Fault with a Bend

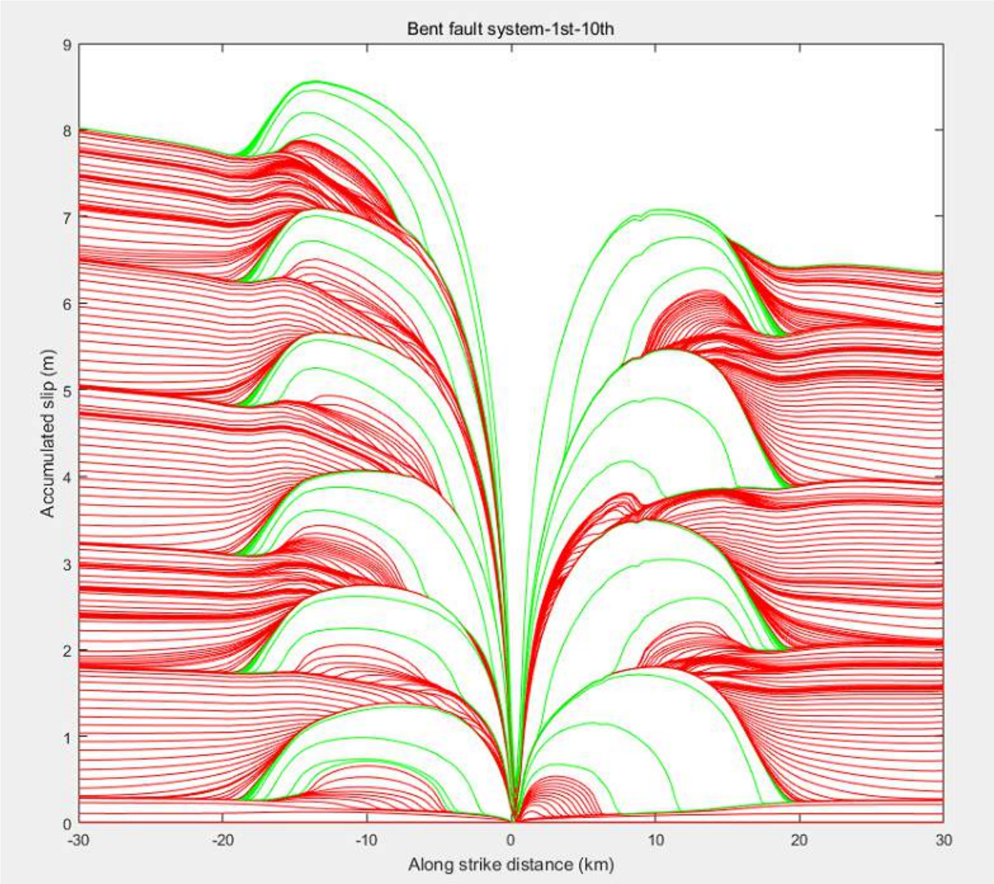
- 10° smooth bend



The fault is 60 km by 30 km.
The yellow velocity weakening region is 30 km by 15 km. The white region is velocity strengthening.

Accumulated slip of the bent system

- The kink serves as a strong barrier to dynamic ruptures. The behavior could be associated with initial stresses, sliprates and state variables.



Concluding Remarks

- **Initial stresses** that are consistent with fault geometry and faulting history **need multi-cycle dynamic simulations**.
- We have **been developing two earthquake simulators that include spontaneous rupture for realistically complex faults** based on FEM methods.
- **The new verification excise will help build confidence** of the community on earthquake cycle simulation studies.