From Single-Event Dynamics to Multicycle Dynamics of Geometrically Complex Faults

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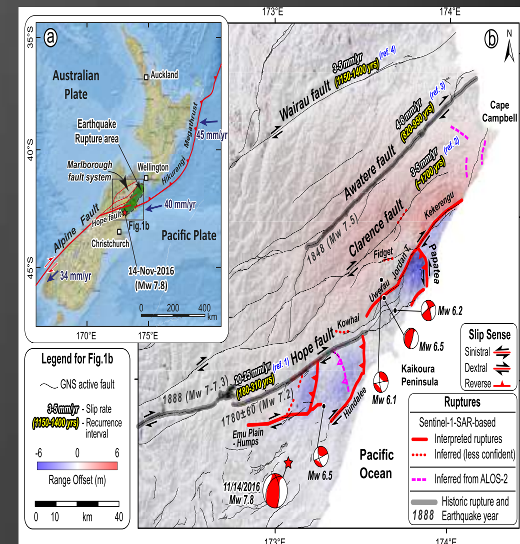
Outline

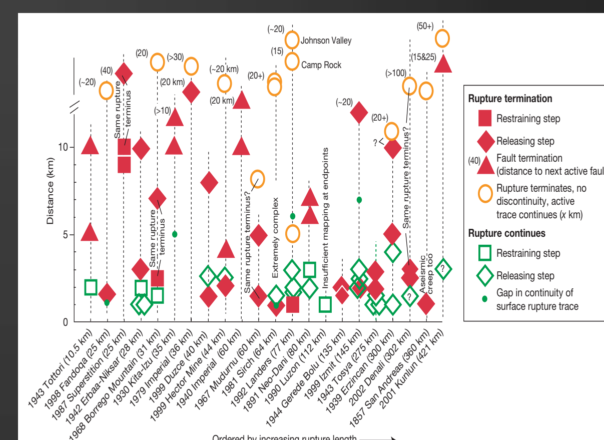
- Background:
  - field & numerical studies
  - single-event vs multicycle dynamics
- A 2D multicycle dynamic model & its application to a real case:
  - Multicycle dynamics of the Aksay Bend along the Altyn Tagh Fault in Northwest China
- Two new 3D FEM-based earthquake cycle simulation methods: Dynamic Earthquake Simulators
- Concluding remarks

Background

- Examples of Complex Ruptures: 1992 Landers,1999 Hector Mine, 1999 Izmit, 2002 Denali, 2008 Wenchuan, 2010 El Mayor- Cucapah, 2016 Kaikoura, …
- Field Studies: Wesnousky (2006, 2008), Biasi and Wesnousky (2016), …
- Single-Event Dynamics: Harris et al. (1991), Harris and Day (1993), Kame et al. (2002), Lozos et al. (2011), …
- Multi-cycle Dynamics: Duan and Oglesby (2005, 2006, 2007), …

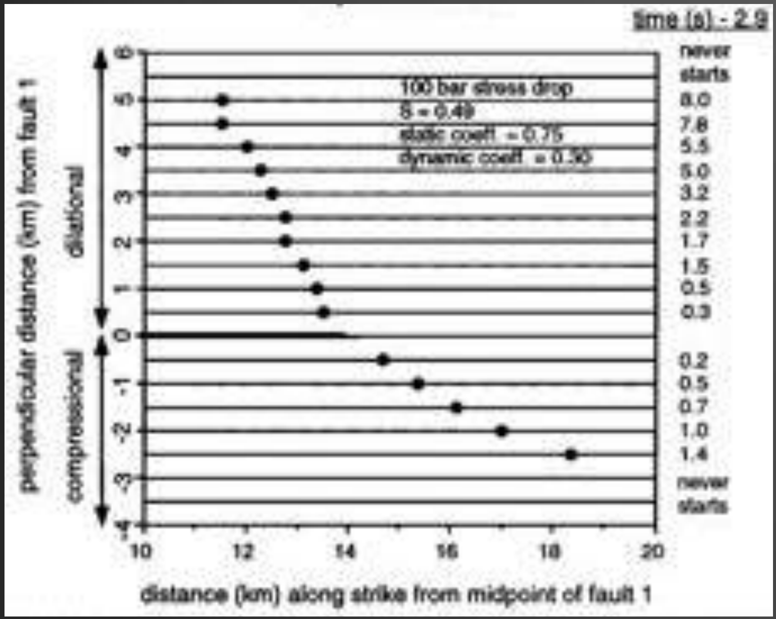


Shi et al. (2017)

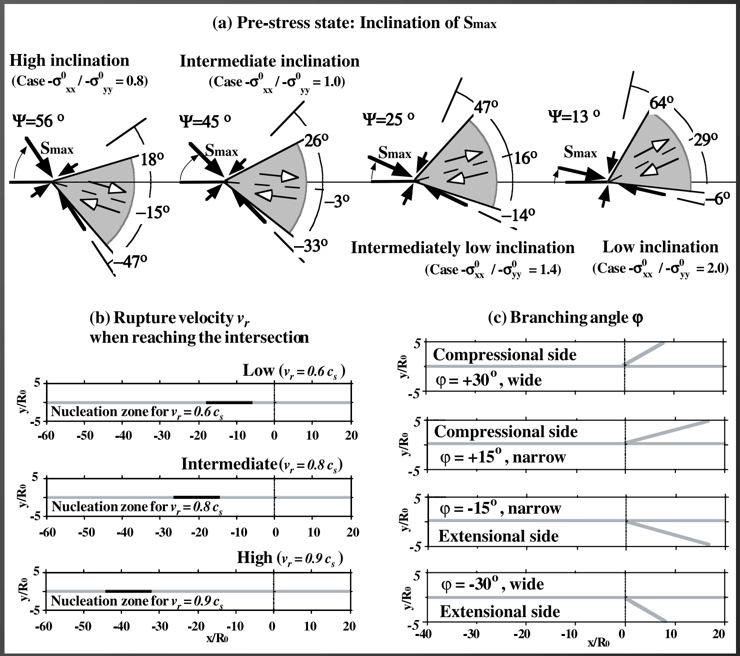


Wesnousky (2006)

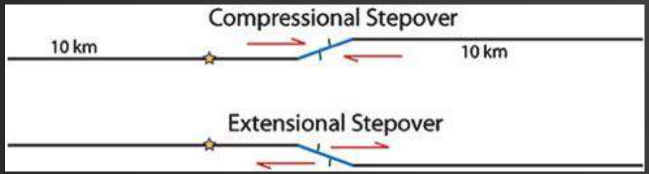
❖ Background: Single-Event Dynamics

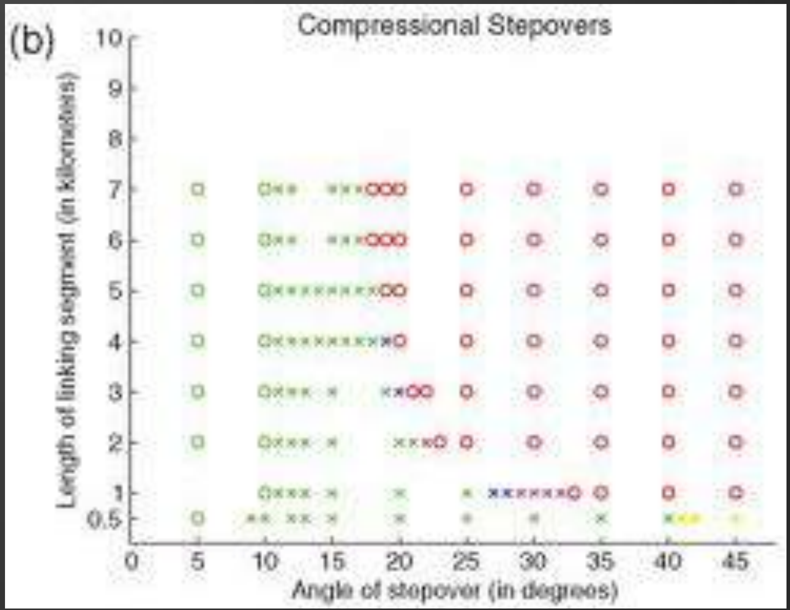


Harris and Day (1993)



Kame et al. (2003)

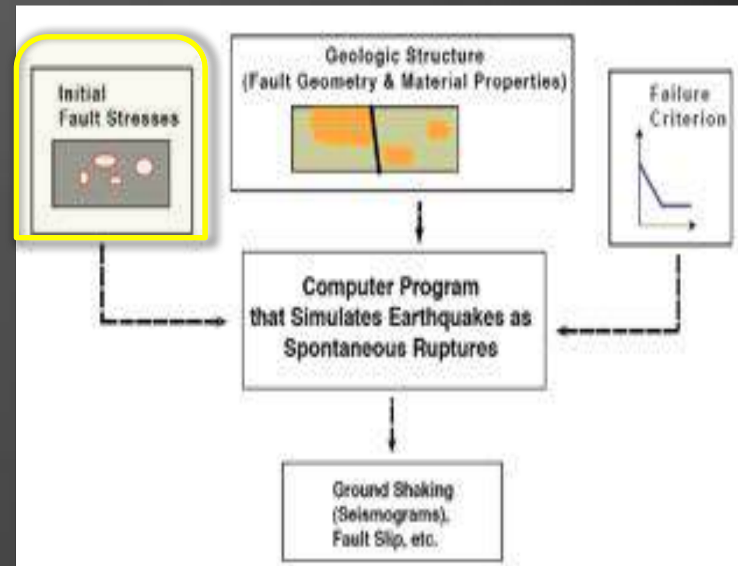




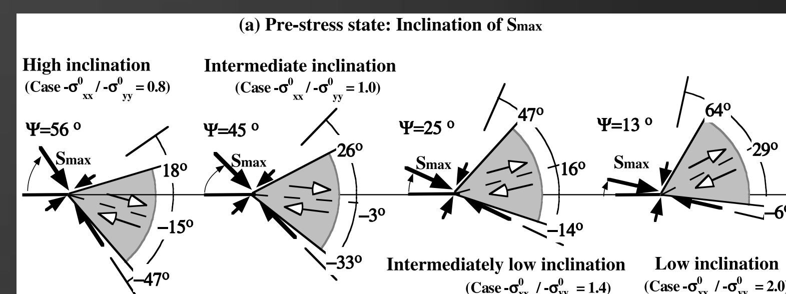
Lozos et al. (2011)

❖ Background: One of Challenges in Single-Event Dynamic models – Assigning Initial Stress

- **Initial stress is a critical ingredient.**
- **Typically a uniform regional stress field is assigned and resolved onto different fault segments.**
- **However, fault stresses near geometrical complexities are heterogeneous due to tectonic loading & previous ruptures.**
- **One way to address the challenge: Multicycle dynamic rupture models:**
  - initial stresses evolve spontaneously and are **consistent with fault geometry and rupture history.**
  - **Different rupture scenarios may occur on a given fault system over multiple cycles: Earthquake Gate!**



Harris et al. (2009)



Kame et al. (2003)

A 2D Multi-cycle Dynamic Model of Complex Faults

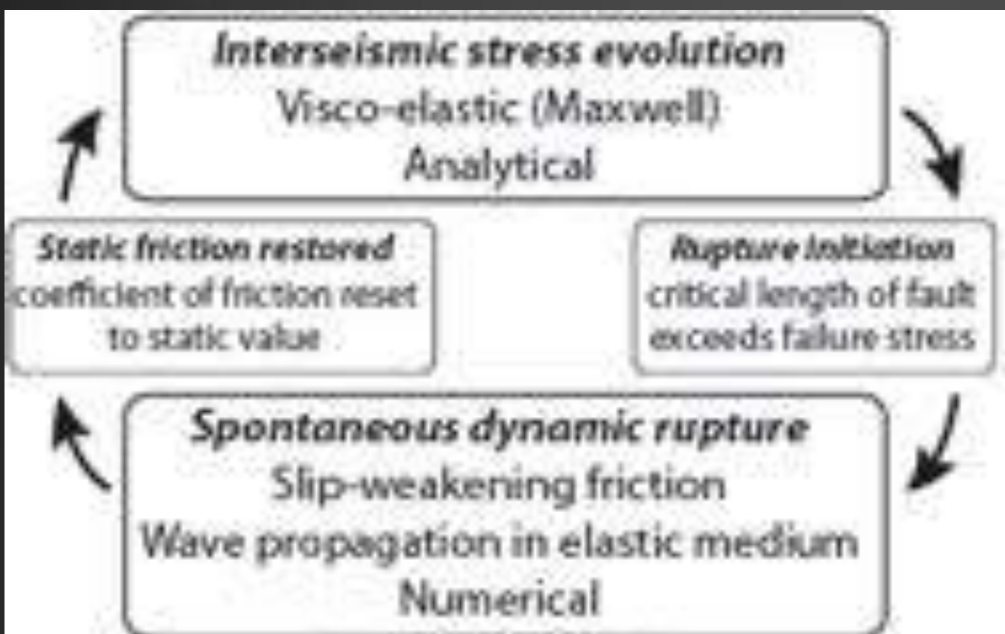
- **Spontaneous rupture models with initial stresses evolved from previous ruptures**
- **Duan & Oglesby (2005, 2006, 2007): Bend, Stepover, Branch**

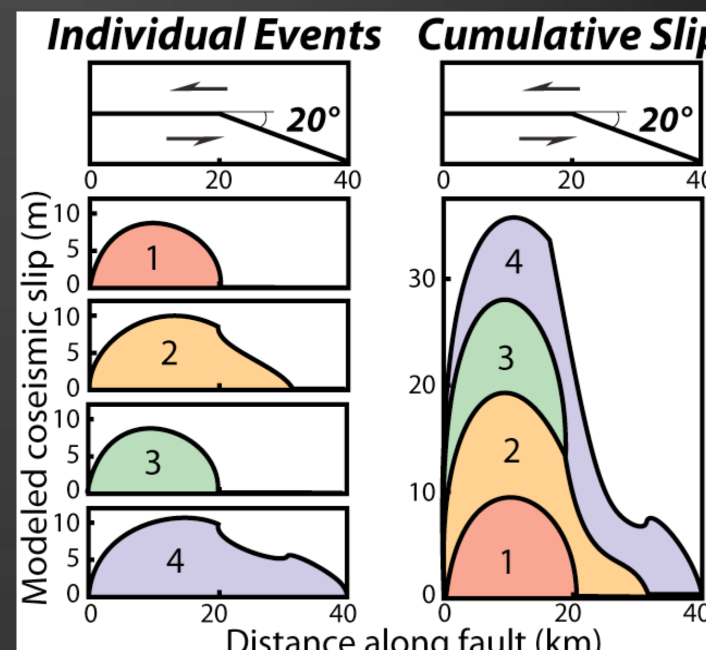
$$\gamma_n = \dot{\varepsilon}\sin(2\theta) \quad , \quad \gamma_\tau = \dot{\varepsilon}\cos(2\theta),$$

$$\sigma_N(t) = (\sigma_N^0 - \sigma^a - \eta\gamma_n)\exp\left(-\frac{\mu}{\eta}t\right) + \eta\gamma_n + \sigma^a$$

$$\sigma_\tau(t) = (\sigma_\tau^0 - \eta\gamma_\tau)\exp\left(-\frac{\mu}{\eta}t\right) + \eta\gamma_\tau$$

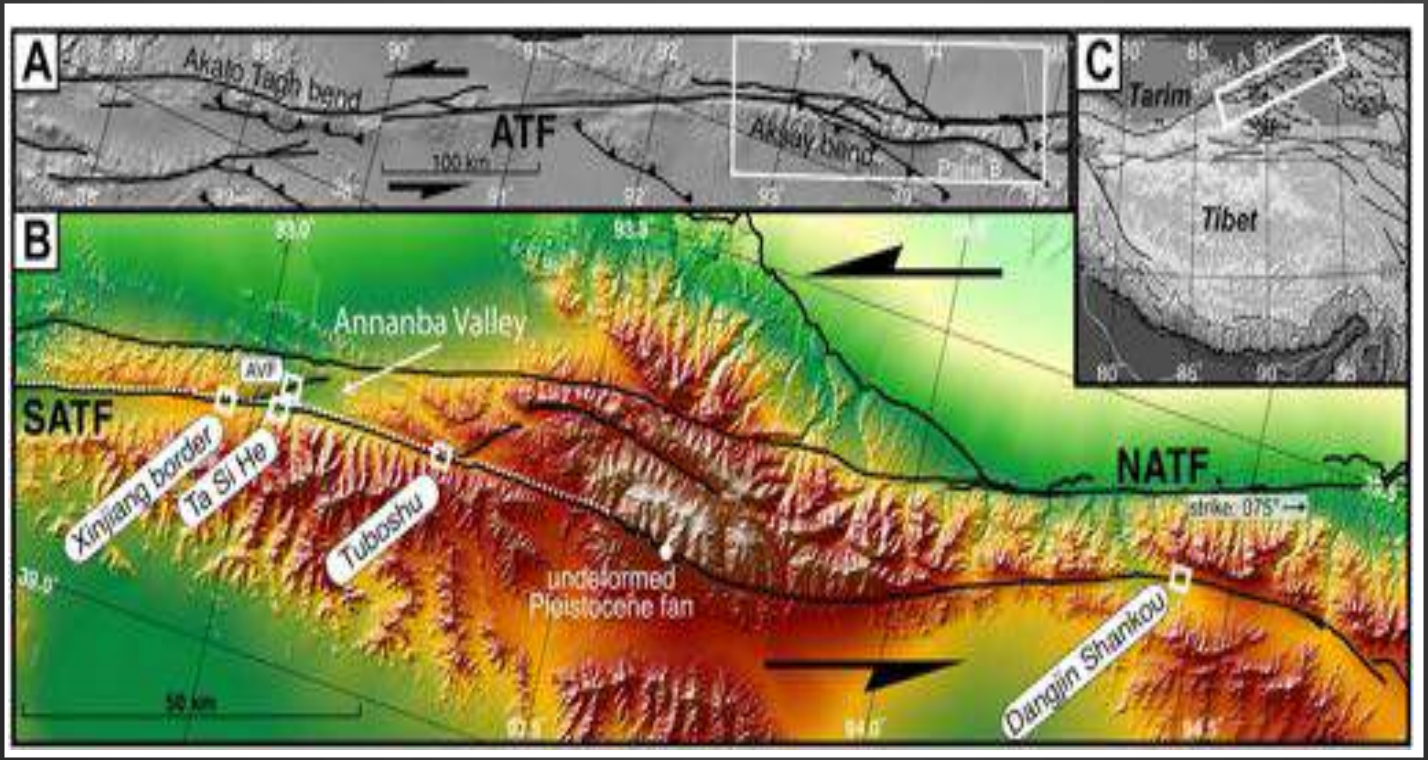
Viscoelastic Model for fault stresses between dynamic events: effects of off-fault deformation (e.g., secondary faulting, uplifting, aftershocks, etc)





EQdyna: An explicit finite element method for dynamic rupture and wave propagation

The Aksay Restraining Bend Along the Altyn Tagh Fault



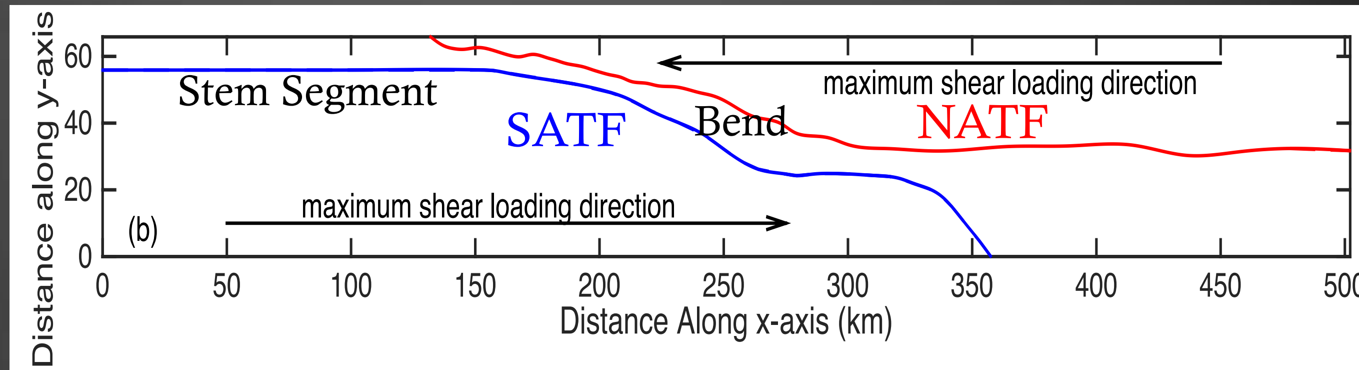
Elliot et al. (2018)

- Two active strands: SATF, NATF
- 200 km long, separated by > 5 km
- Restraining
- Mountains with peaks > 5.5 km

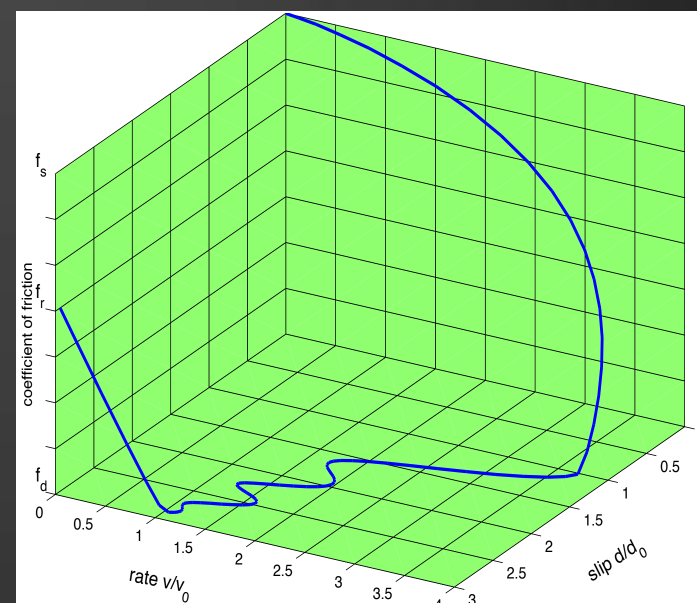
❖ A Case Study

Models of the Aksay Bend

- **Fault geometry**
- **Friction laws**: slip- & rate-weakening
- Other parameters: **viscosity**, stress relaxation over cycles



Model	Viscosity (Pa s)
A	2.5×10^{22}
B	2.2×10^{22}
C	2.8×10^{22}

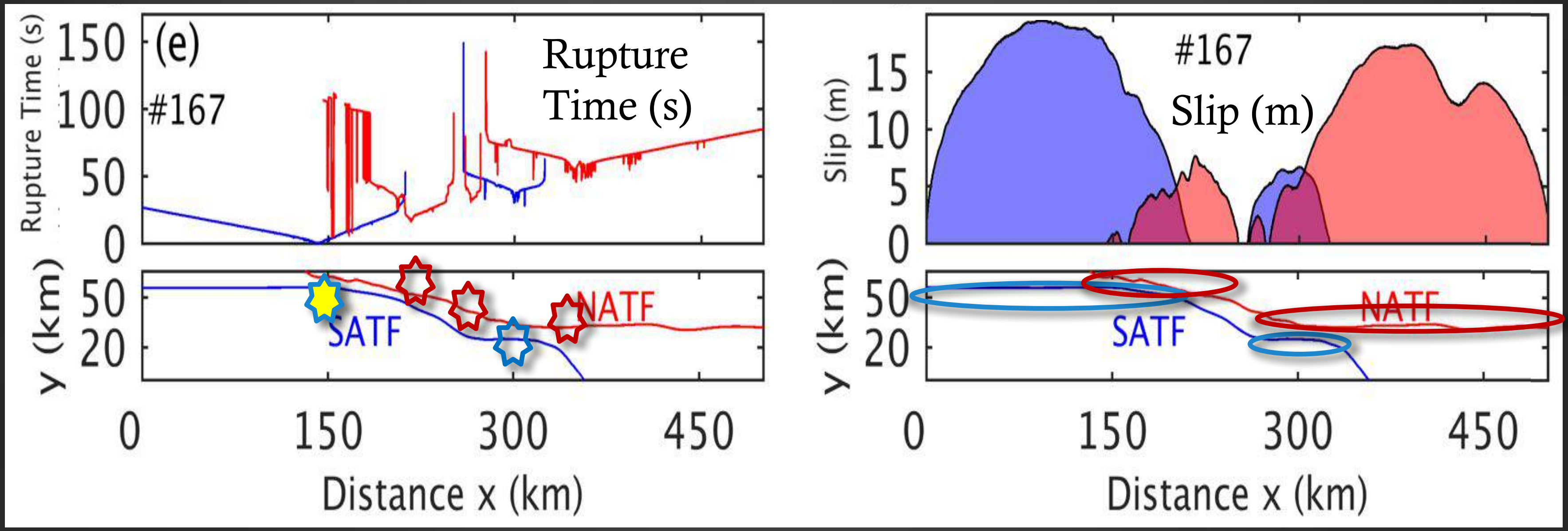


❖ A Case Study: Duan et al. (2018)

What Kinds of Ruptures can Occur on the Fault Over Cycles?

- One example:

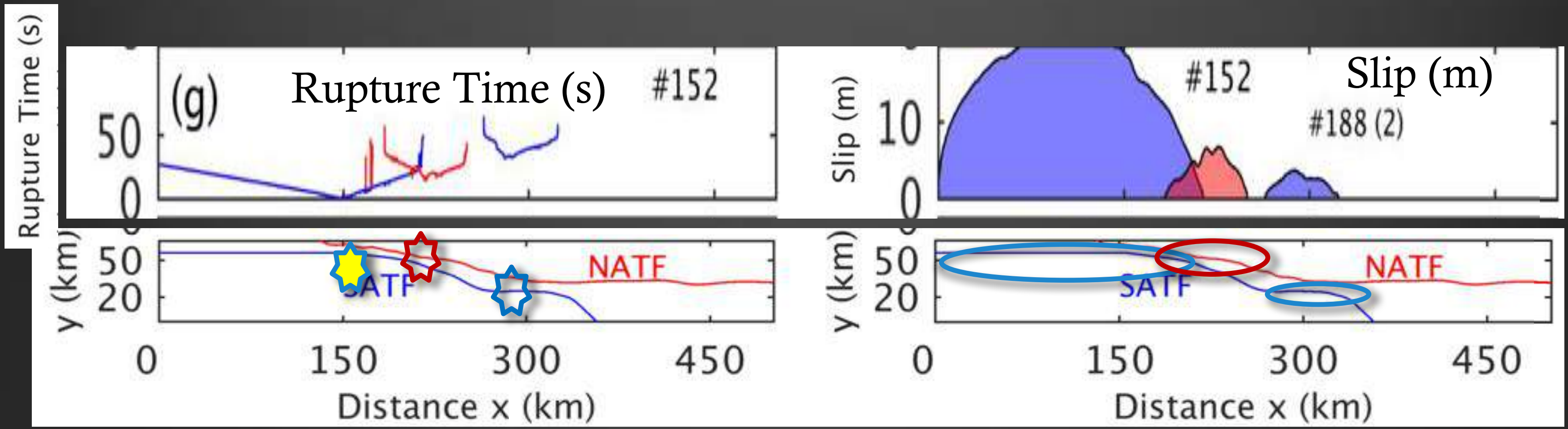
❖ Duan et al. (2018)



- Ruptured most parts of the fault system: two stems + some part of the bend - Jumping rupture (The EQ gate opens).
- Unbroken patchs between slipping patches.
- Non-continuous rupture propagation even on one segment: triggering

What Kinds of Ruptures can Occur on the Fault Over Cycles?

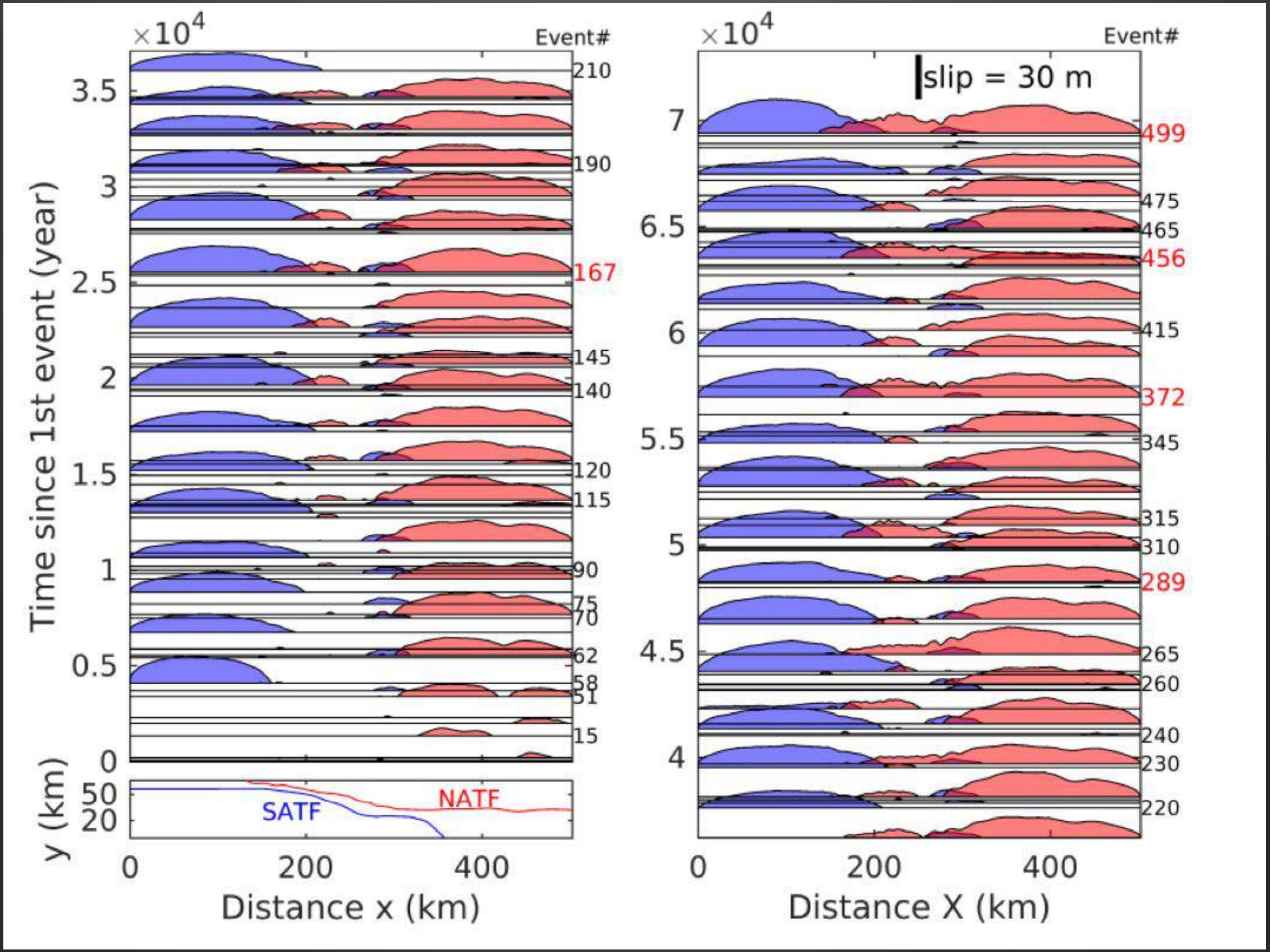
- Another example:



- Ruptured one stem segment + some small portions within the bend: not onto the other stem segment – not a jumping rupture (Gate closed)
- Slip in one event on both strands may not necessary be a giant event!
- Combination of dynamic + static effects

❖ Duan et al. (2018)

Overall Event Patterns Over 500 cycles: Model A



❖ Duan et al. (2018)

How Effective is the Aksay Bend EQ Gate in Stopping Ruptures?

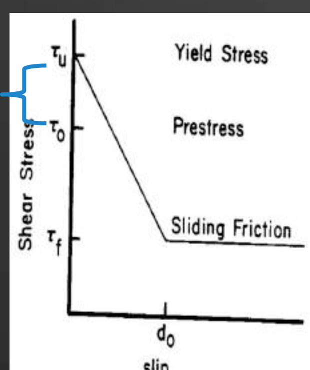
- Jumping ruptures: as in the first example, ruptured both stem segments and some portions of the bend.
- Among meaningful events (excluding tiny events) from different models, we find:
  - About 10% percent are jumping ruptures.
  - About 90% ruptures from either side of the bend stop at the bend.
- The EQ gate is an effective gate to stop dynamic ruptures.

❖ Duan et al. (2018)

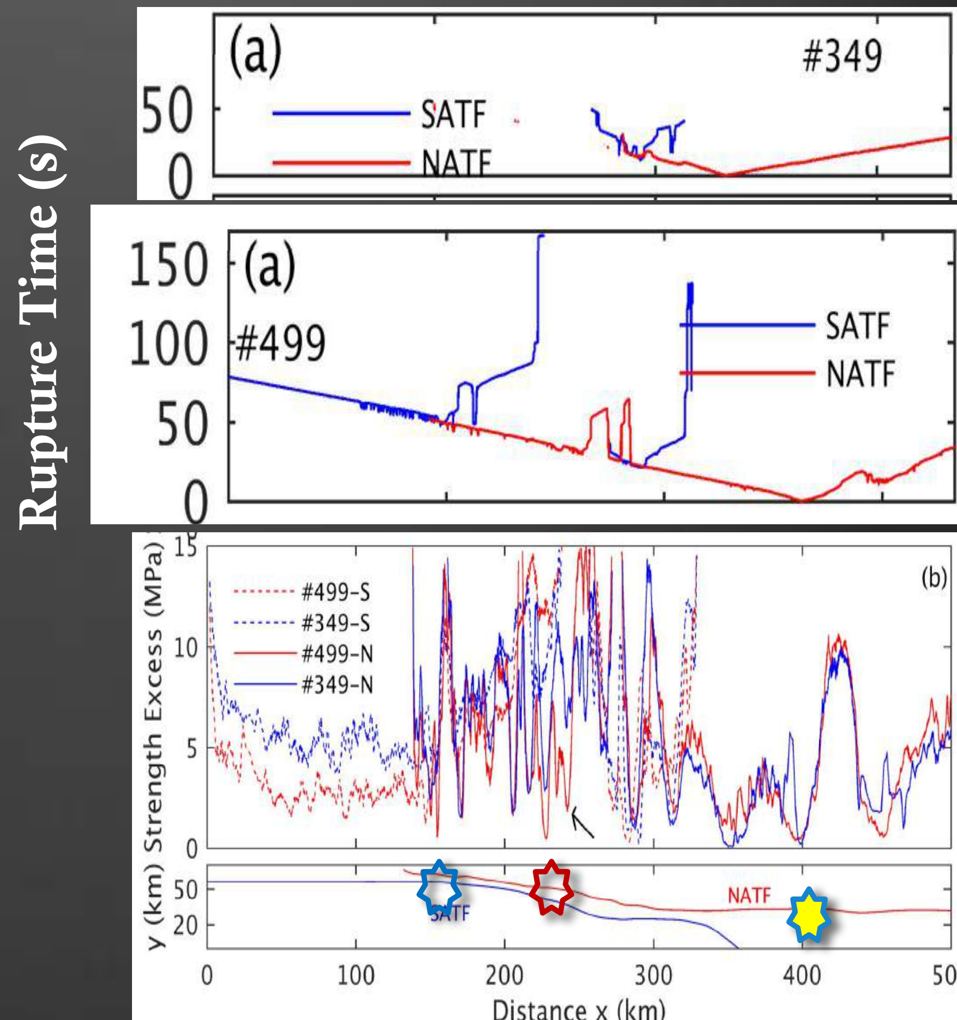
Under What Conditions is the EQ Gate open?

- Low strength excess patches are well developed: close enough for triggering to happen!

Strength excess



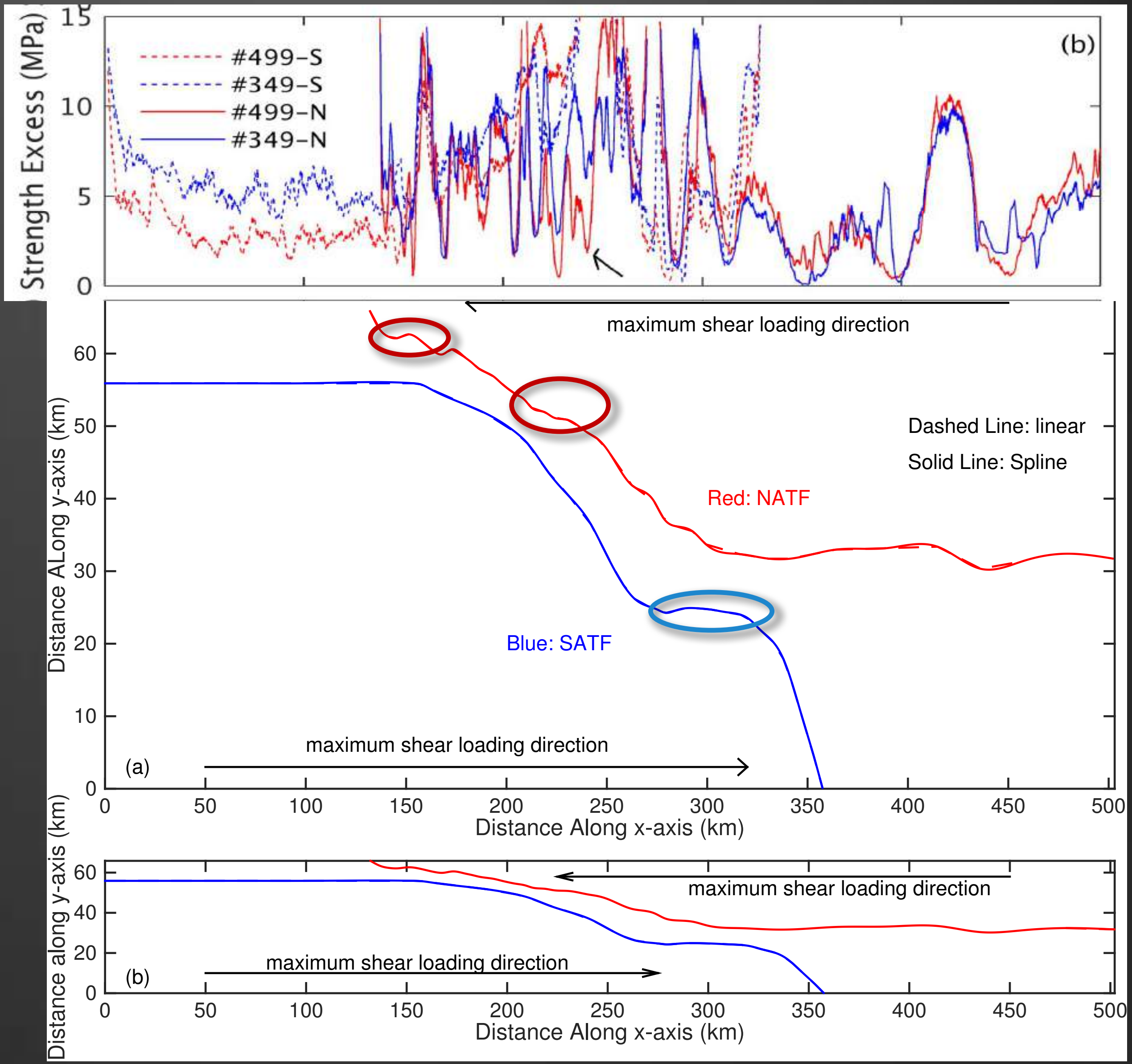
Strength excess = yield stress – prestress



❖ Duan et al. (2018)

How are the Conditions achieved?

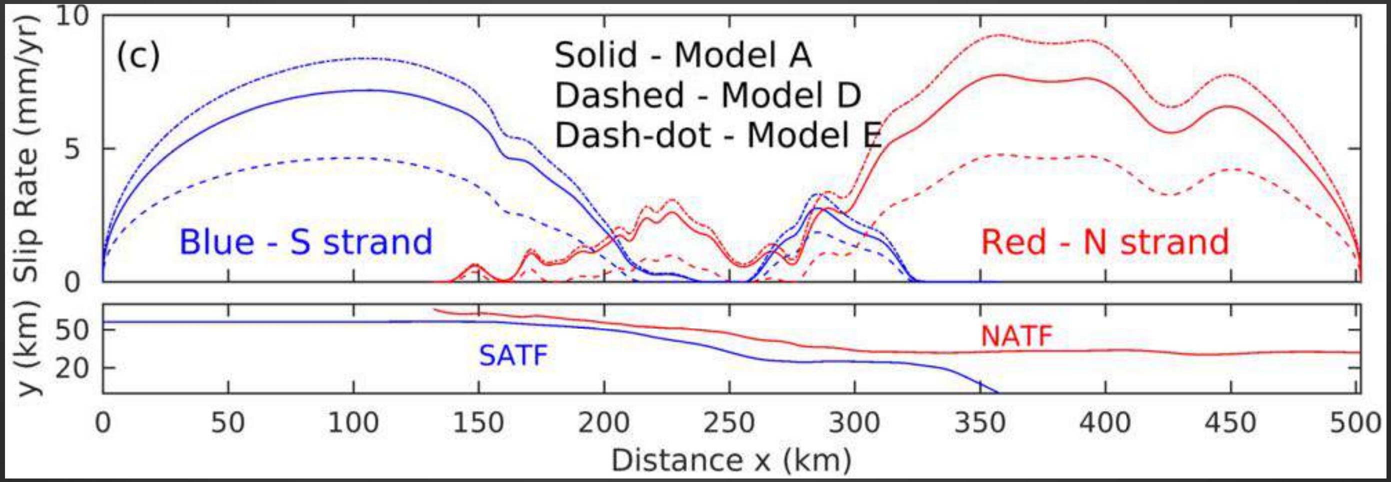
- **Secondary favorably oriented portions** within the largely unfavorably oriented bend



❖ Duan et al. (2018)

Model Results can be Compared with Paleoseismic Observations

- Slip rate: accumulated slip over many cycles divided by times for these cycles.



- Recurrence intervals of large events

❖ Duan et al. (2018)

- These are ongoing works.

Conclusions

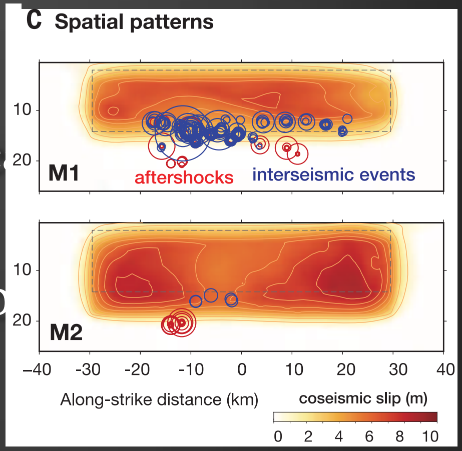
- **The** multi-cycle dynamic **models** provide a means to explore **potential rupture patterns** on realistically complex faults.
- The Aksay bend can **halt 90% large ruptures** propagating from either side of the bend.
- Well-developed low-strength excess **patches** within the bend allow the earthquake gate to open occasionally.
- **Secondary favorably oriented segments** within the bend play critical roles for ruptures to occasionally jump across the bend.

❖ Duan et al. (2018)

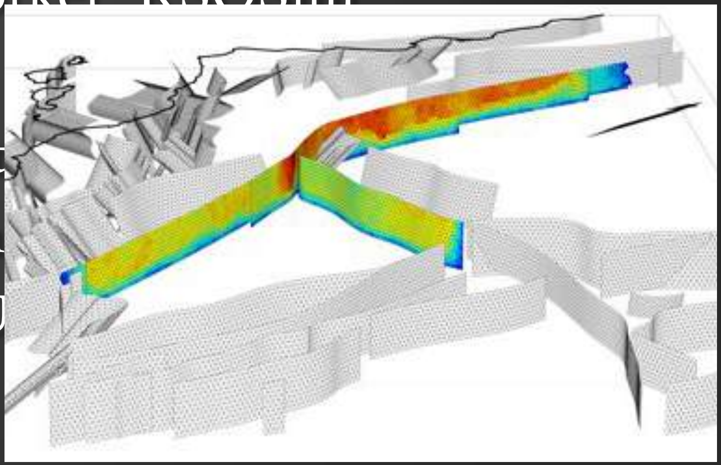
Existing 3D Earthquake Cycle Simulators in the Community

- Lapusta and co-worker: Boundary Integral
  - Fully dynamic for co-seismic rupture process
  - All other quasi-static phases: interseismic, nucle postseismic
  - Limited to vertical strike-slip planar faults, unifo media.

Jiang and Lapusta (2016)



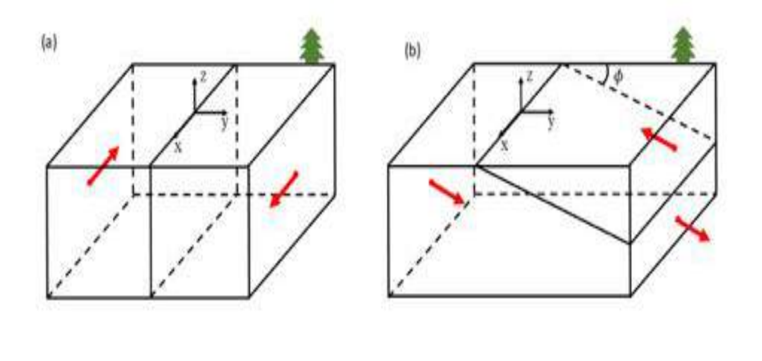
- Dieterich at UC Riverside and co-worker: RSQSim
  - Boundary Element
  - Not fully dynamic for co-seismic rupt
  - Applicable for complex faults, still un
  - Being used for CA hazard analysis: U

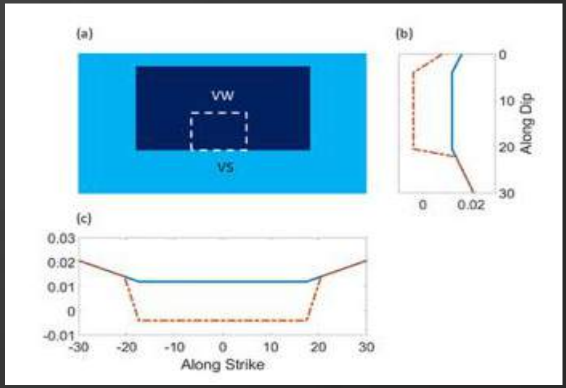


❖ Review: Existing Earthquake Simulators

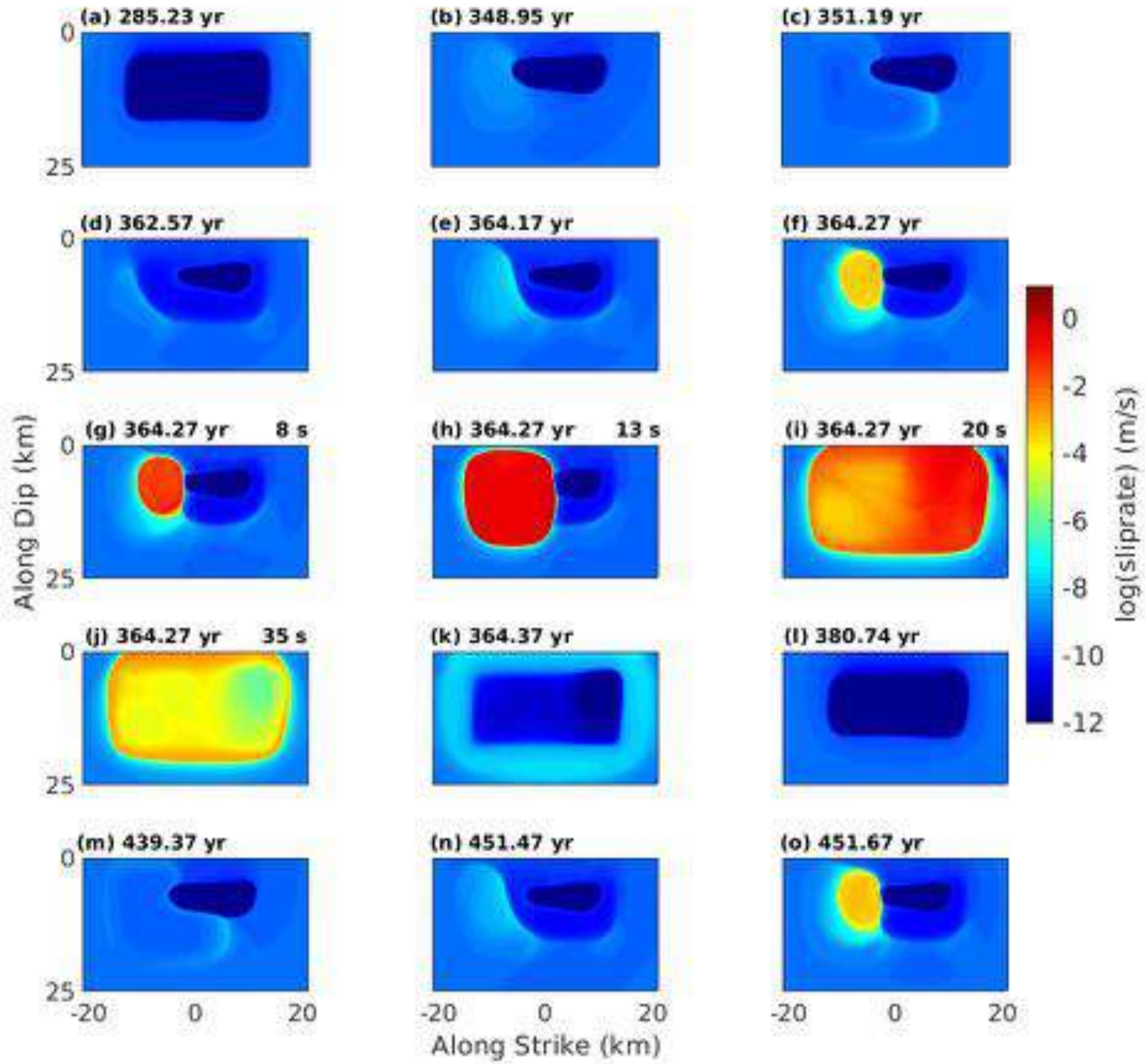
One New 3D Dynamic Earthquake Simulator

- Luo, Duan, and Liu (2018, JGR, in revision)
- EQdyna-based earthquake simulator
- EQdyna: an explicit finite element method for dynamic rupture and seismic wave proapgation
- EQdyna + Dynamic Relaxation Technique: use the dynamic solver to obtain solutions for quasi-static processes



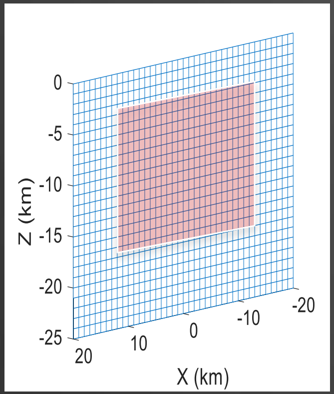


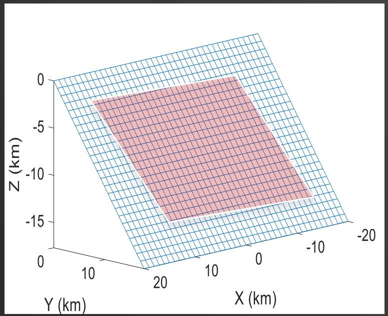
❖ A first 3D FEM-based Dynamic Earthquake Simulator

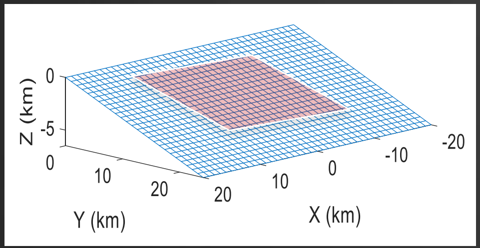


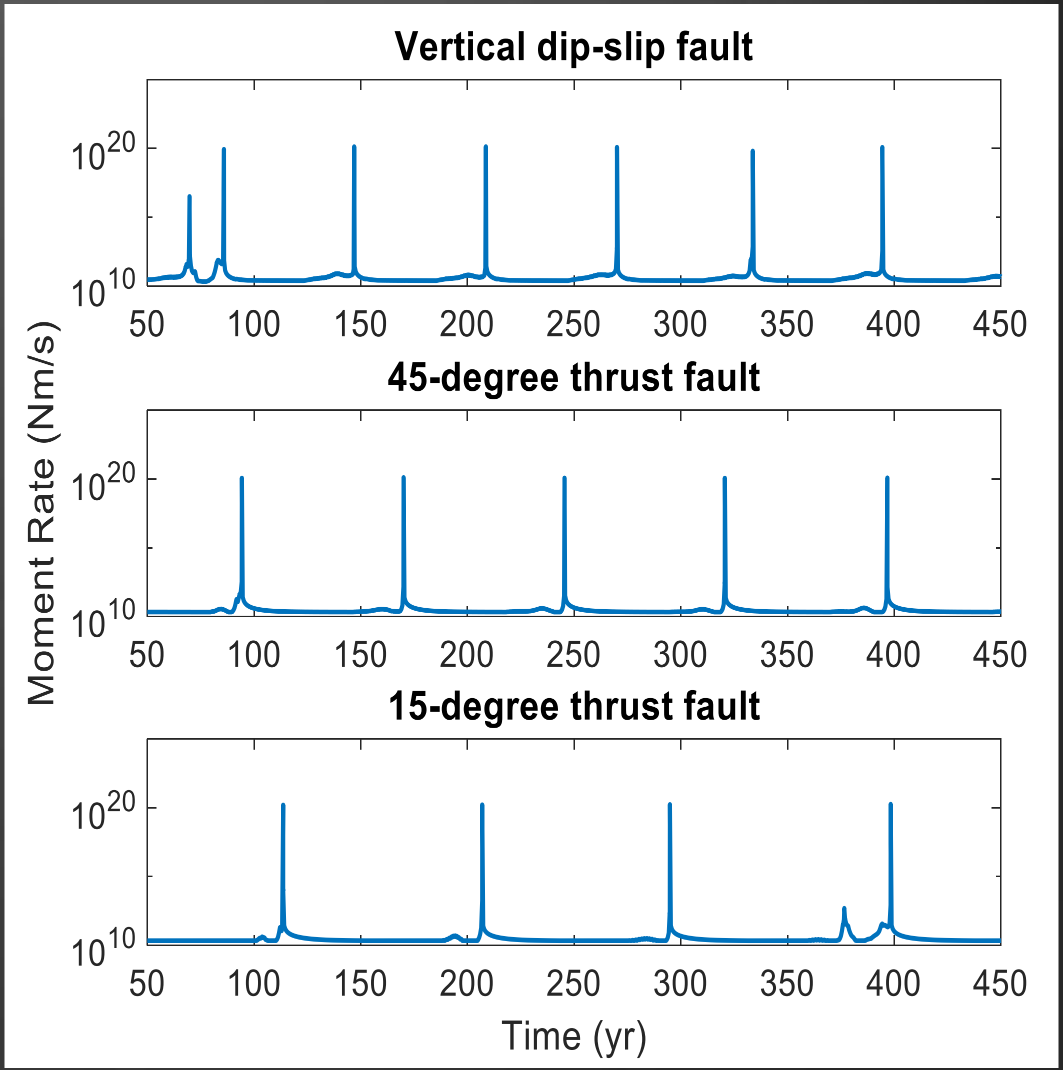
❖ A first 3D FEM-based Dynamic Earthquake Simulator

Moment Rate Function









❖ A first 3D FEM-based Dynamic Earthquake Simulator

Another New 3D Dynamic Earthquake Simulator

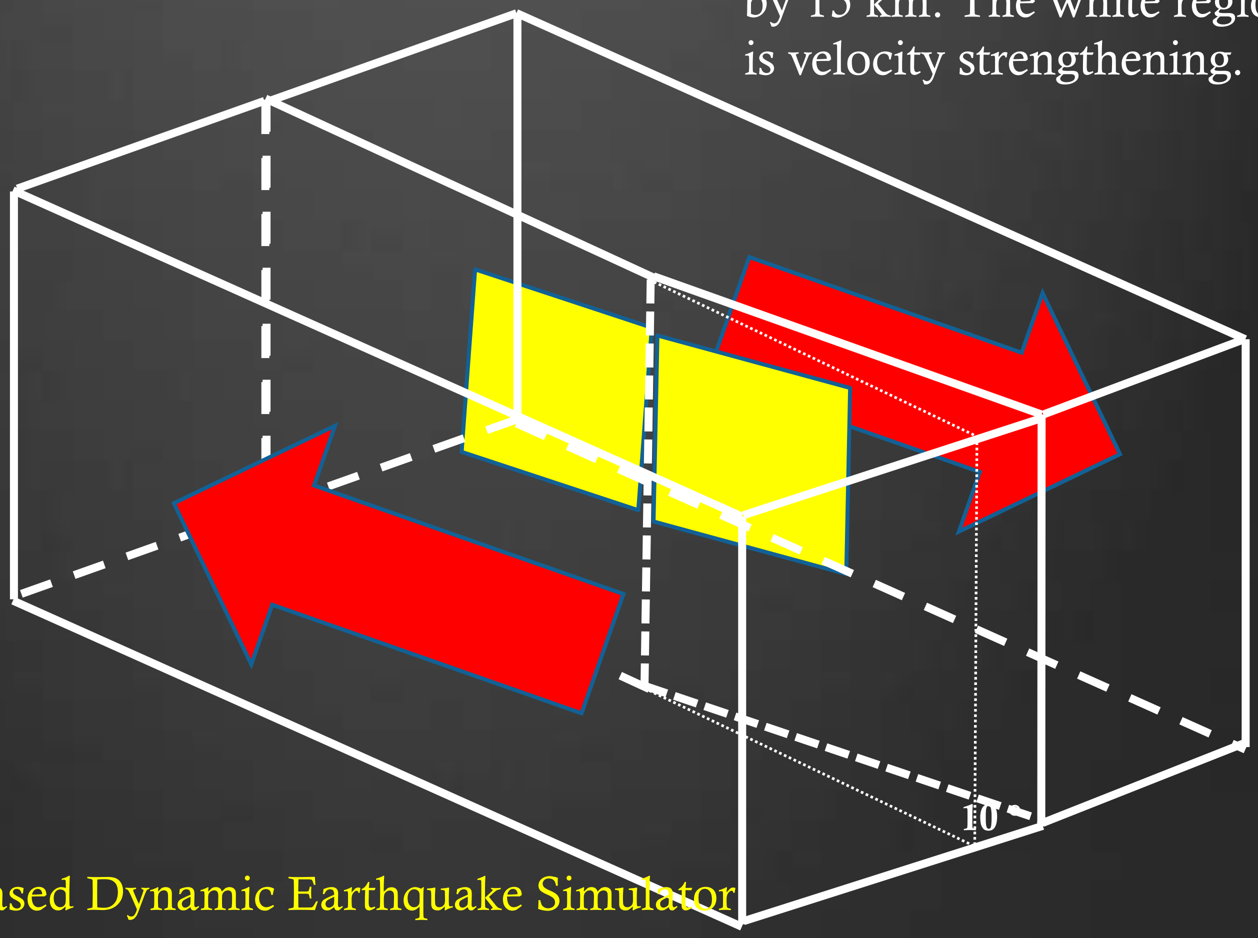
- Liu, Duan, and Luo (2018, in preparation)
- EQdyna: an explicit dynamic FEM for coseismic
- EQquasi: an implicit static FEM for interseismic, nuleation, and postseismic quasistic processes
- EQdyna + EQquasi for earthquake cycle simulations

❖ A Second 3D FEM-based Dynamic Earthquake Simulator

Strike-slip Fault with a Bend

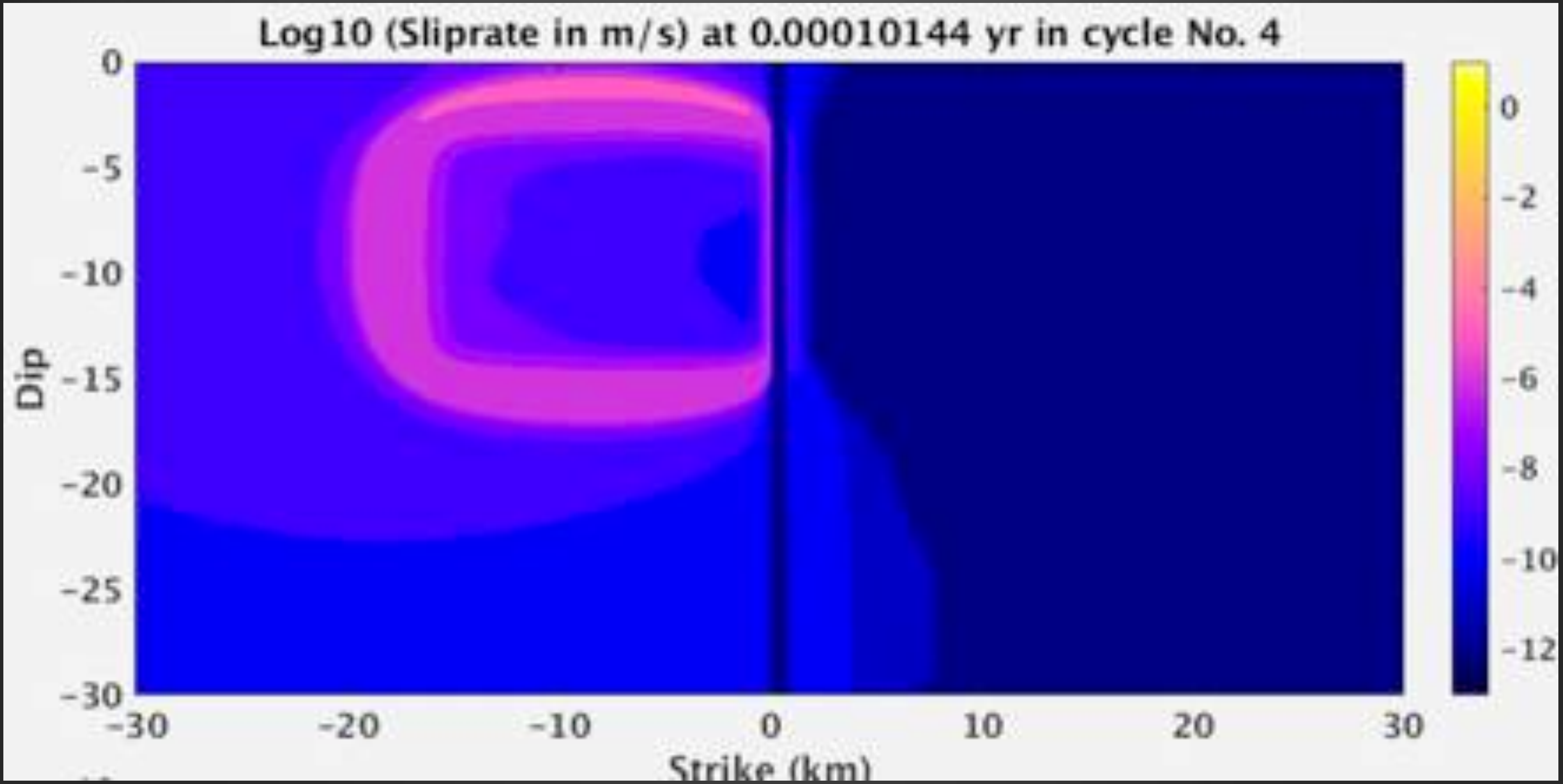
- 10° smooth bend

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.



❖ A Second 3D FEM-based Dynamic Earthquake Simulator

Earthquake cycles on the bent fault



❖ A Second 3D FEM-based Dynamic Earthquake Simulator

Concluding Remarks

- **Initial stresses for dynamic rupture models** that are consistent with fault geometry and faulting history **need multi-cycle dynamic simulations**.
- We have **been developing two 3D dynamic earthquake simulators that include spontaneous rupture for realistically complex faults** based on FEM methods.
- **Applications of the FEM-based dynamic earthquake simulators** will allow us to explore many earthquake scientific questions on realistically complex fault systems, in particular examining potentials for occasionally extreme events that break multi-faults.