Stress Heterogeneity and Dynamic Rupture Along Geometrically Complex Faults

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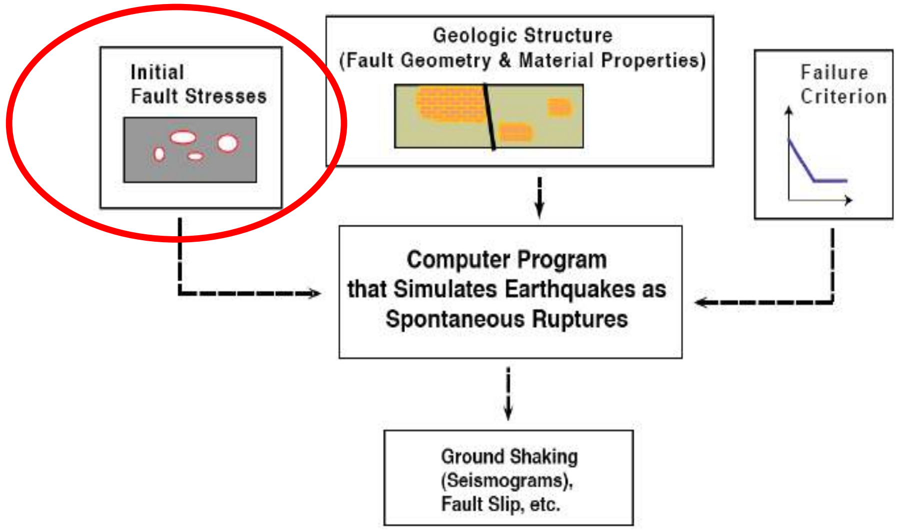
Outline

- Introduction: Initial fault stress (pre-stress) in dynamic rupture models
- 2D multicycle dynamic models of geometrically complex faults
  - Methodology
  - Idealized models: bend, stepover, branch
  - A real case: the Aksay bend along the Altyn Tagh Fault
- Recent efforts on 3D dynamic earthquake simulators
- Concluding remarks

Ingredients in a dynamic rupture model

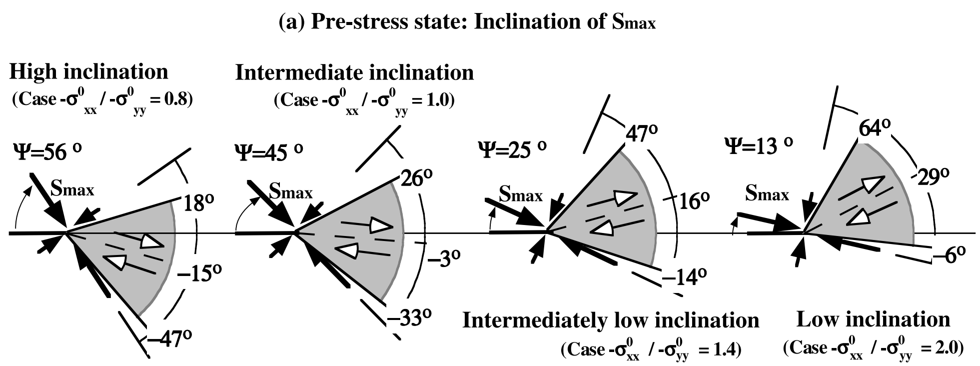
- Harris et al. (2009):



- Pre-stress (initial stress) is one of three essential ingredients, probably least constrained but very important!

Common practices in assigning initial stresses

- Typically, **a uniform regional stress field** is assigned and is then resolved onto different fault segments. E.g.,



Kame et al. (2003): dynamic branching

Common practices in assigning initial stresses (cont'd)

- Earlier/some models: homogeneous stresses on all fault segments.
- Self-similar initial stresses: mainly for ground motion prediction.
- Ad-hoc heterogeneous initial stresses to re-produce rupture patterns of real events.
- …

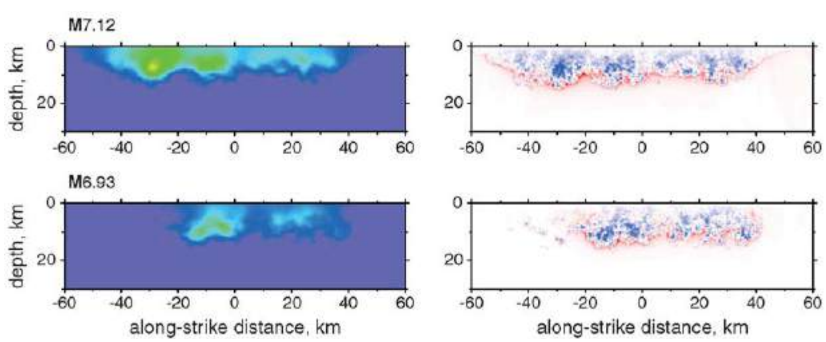


Figure 3. Slip (left) and change of shear stress (right) at the end of the dynamic calculation in five different random realizations of the heterogeneous high-stress model.

Andrews & Barall (2011): for realistic ground-motion prediction

Oglesby et al. (2004): the 2002 Denali model

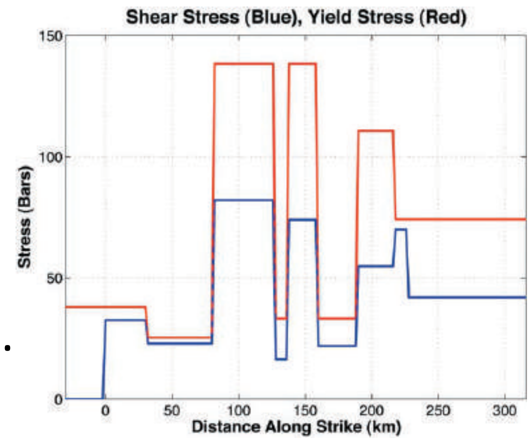


Figure 13. Shear and yield prestresses for the preferred heterogeneous stress model (model PREFERRED in Table 4) plotted along the dashed line in Figure 12. Yield stress can be thought of as a proxy for normal stress. Note that this stress field is far more heterogeneous than is attributable to any unmodeled geometrical effects in this fault system.

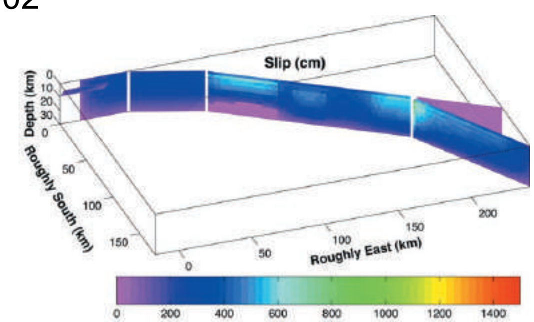


Figure 14. Final slip pattern for the preferred heterogeneous stress model (model PREFERRED in Table 4). Slip abandons the Denali fault east of the fault

Is the fault pre-stress heterogeneous?

- Very likely, particularly on geometrically complex faults.
- Models that aim to fit observed rupture & slip patterns typically require some sort of initial stress heterogeneity.

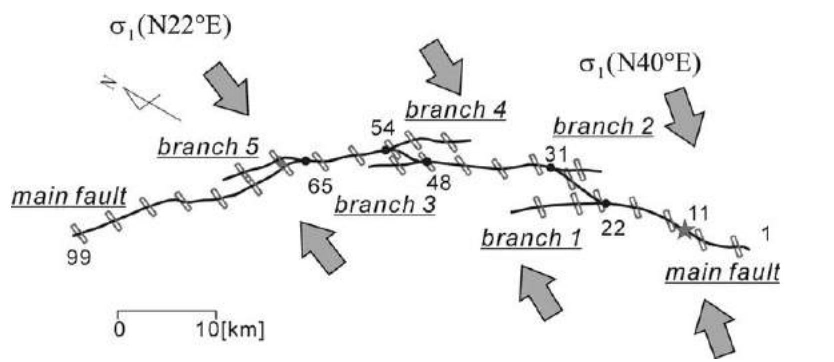
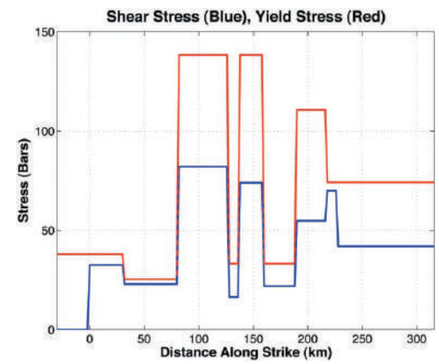


Figure 3. Maximum principal stress σ_1 assumed in this study. Directions (bars) are shown along the fault system

Aochi & Fukuyama (2002): the 1992 Landers model

Oglesby et al. (2004): the 2002 Denali model



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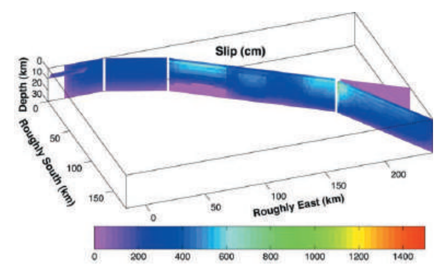
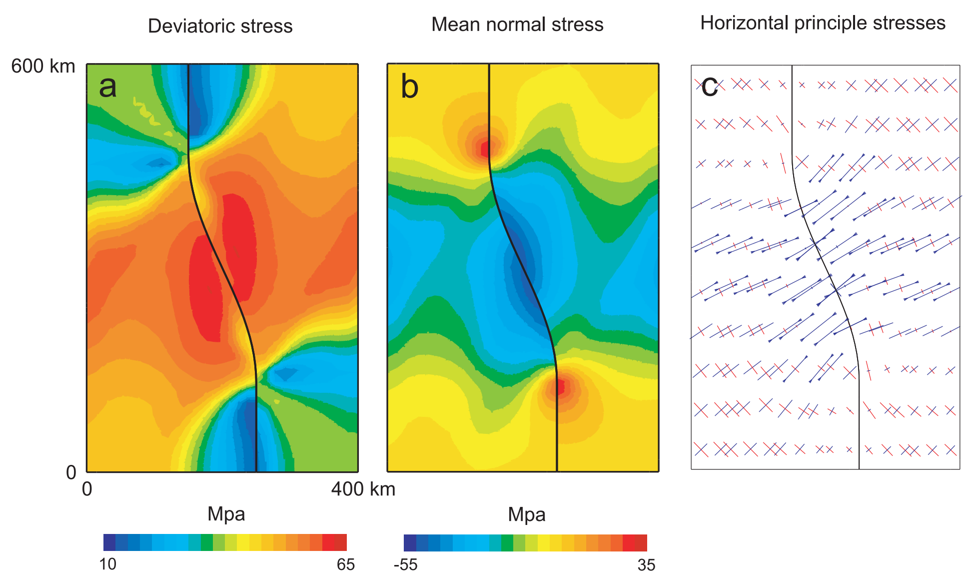


Figure 14. Final slip pattern for the preferred heterogeneous stress model (model PREFERRED in Table 4). Slip abandons the Denali fault east of the fault

Is the fault pre-stress heterogeneous? (cont'd)

- Mechanical analyses show heterogeneous stress at fault complexities:
  - ➢E.g., Stress perturbations by a fault bend in the steady state of a viscoelastoplastic model

Li et al. (2009)

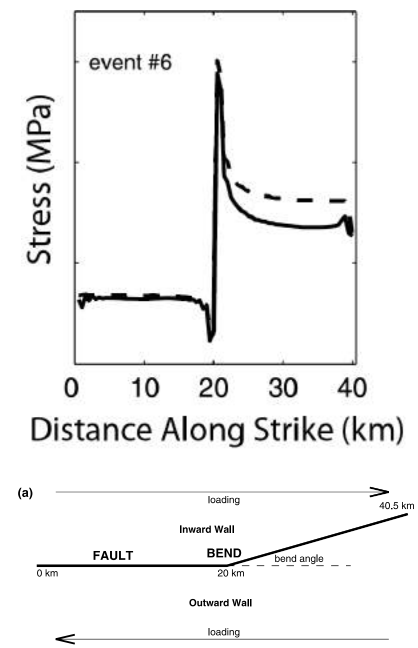


How to systematically capture heterogeneous fault pre-stresses in dynamic rupture models?

- Putting dynamic rupture models into earthquake cycle simulations:
  - Multicycle dynamic models (e.g., Dynamic earthquake simulators)

- Stress at fault complexities will be built up over multiple earthquake cycles in a purely elastic model.

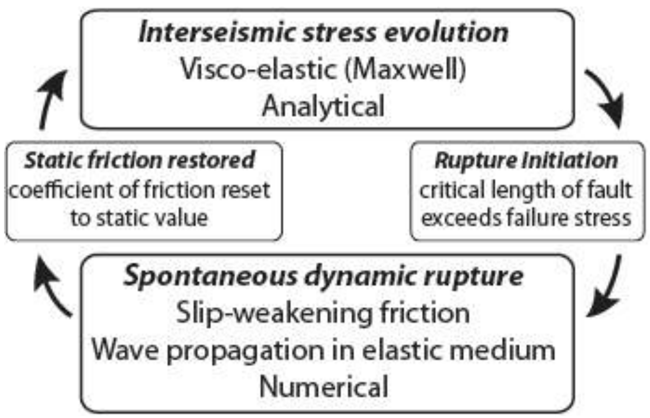
- Some sort of stress relaxation is needed to avoid pathological fault stress buildup at fault complexities: off-fault deformation, aftershocks, etc.



Duan and Oglesby (2005)

A 2D Multicycle dynamic models

- Interseismic fault stress evolution: a viscoelastic model with analytical solutions (Nielsen & Knopoff, 1998; Duan and Oglesby, 2005).
- Coseismic dynamic rupture simulations by finite element methods (FEM): EQdyna.
- A 2D multicycle dynamic model of complex faults: Duan & Oglesby (2005, 2006, 2007).

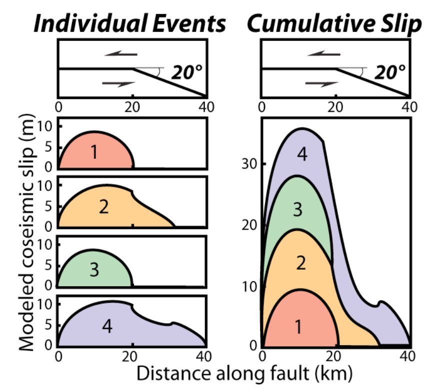


$$\sigma_N(t) = (\sigma_N^0 - \sigma^a - \eta\gamma_n)\exp\left(-\frac{\mu}{\eta}t\right) + \eta\gamma_n + \sigma^a$$

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

Modified from Duan & Oglesby (2005)

➢ **Different rupture behaviors on a given complex fault** because of **different initial stresses over multiple EQ cycles**: **Earthquake Gate!**

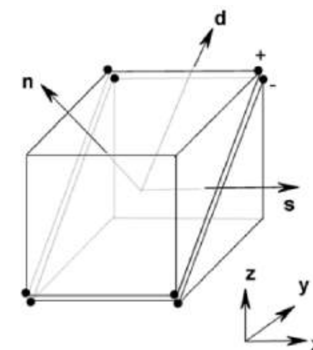


EQdyna: An Explicit FEM Code

for Rupture Dynamics & Wave Propagation

(Duan & coworkers, 2005-2019)

$$\rho u_{i,tt} = \sigma_{ij,j} + f_i \qquad \mathbf{Ma} + \mathbf{Cv} + \mathbf{Ku} = \mathbf{F}$$



- Faulting by Traction-at-Split-Node (TSN): Day et al., 2005; Duan, 2010.
  - Discontinuity of displacement
  - Interaction through traction: shear traction bounded above by frictional strength

$$\tau \le \tau_c$$

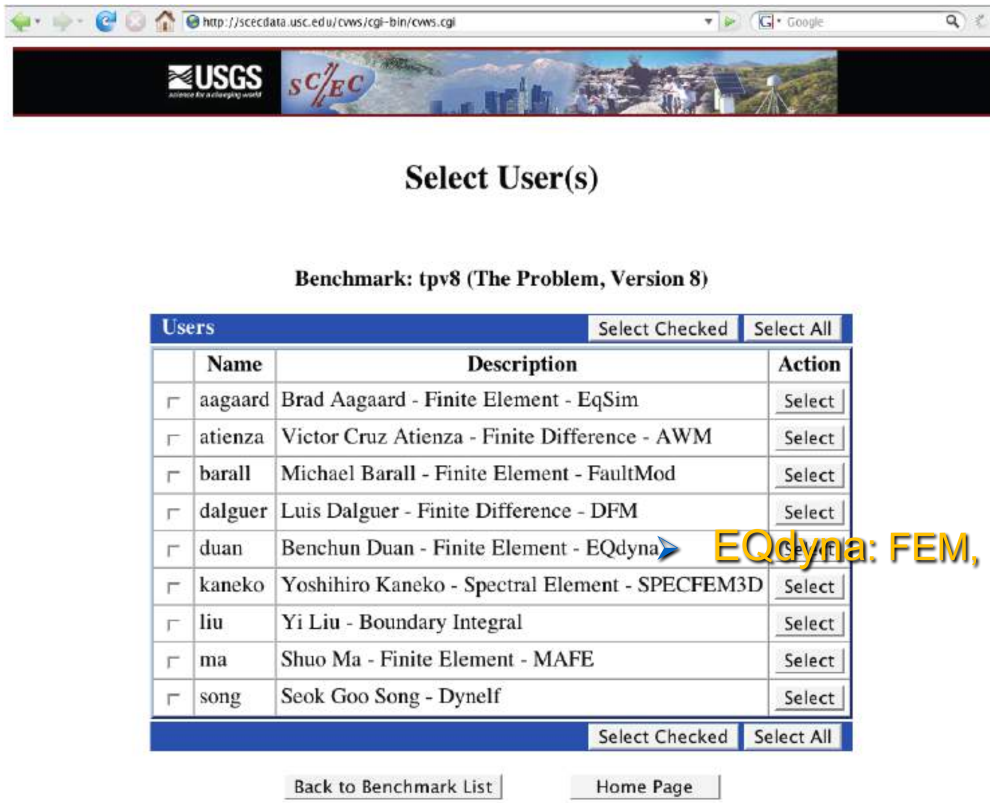
$$(\tau - \tau_c)\dot{s} = 0$$

$$\tau_c = -\mu(s, \dot{s}, \theta)\sigma_n$$

- Friction Laws:
  - Slip-weakening law
  - Slip- & rate- weakening law: Duan et al. (2019)
  - Rate- & state- dependent law: Luo and Duan (2018)

SCEC Code Validation

http://scecdata.usc.edu/cvws



http://scecdata.usc.edu/cvws/cgi-bin/cvws.cgi

Select User(s)

Benchmark: tpv8 (The Problem, Version 8)

Users — Select Checked | Select All

	Name	Description	Action
	aagaard	Brad Aagaard - Finite Element - EqSim	Select
	atienza	Victor Cruz Atienza - Finite Difference - AWM	Select
	barall	Michael Barall - Finite Element - FaultMod	Select
	dalguer	Luis Dalguer - Finite Difference - DFM	Select
	duan	Benchun Duan - Finite Element - EQdyna	Select
	kaneko	Yoshihiro Kaneko - Spectral Element - SPECFEM3D	Select
	liu	Yi Liu - Boundary Integral	Select
	ma	Shuo Ma - Finite Element - MAFE	Select
	song	Seok Goo Song - Dynelf	Select

Select Checked | Select All

Back to Benchmark List | Home Page

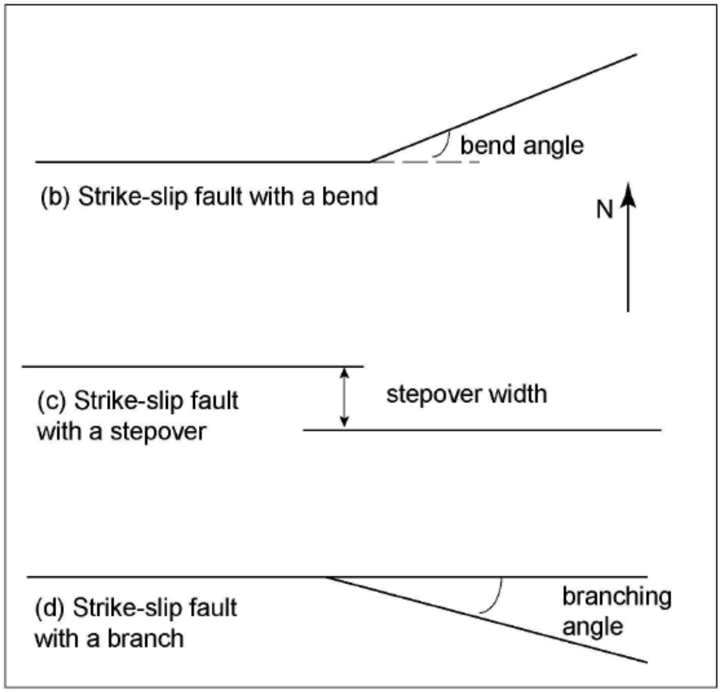
EQdyna: FEM, Duan& co-workers (2005-2019)

2D Multicycle Dynamics of Idealized Models

- Faults with a bend:
  Duan & Oglesby (2005)

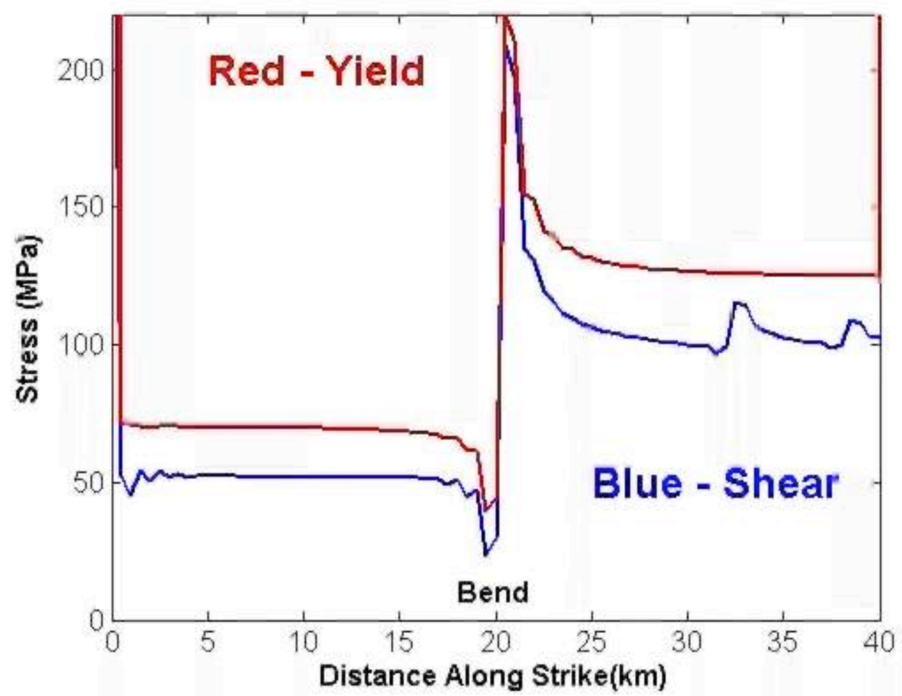
- Faults with a stepover:
  Duan & Oglesby (2006)

- Faults with a branch:
  Duan & Oglesby (2007)

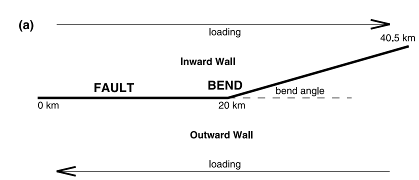


Faults with a sharp bend (kink)

- Heterogeneous fault stresses
- Initiation/termination at kinks
- Unilateral/bilateral ruptures
- Time delay at kinks
- Dynamic interaction of two segments

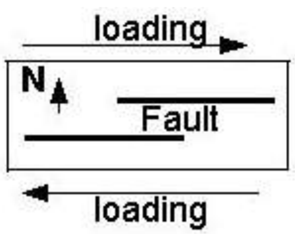


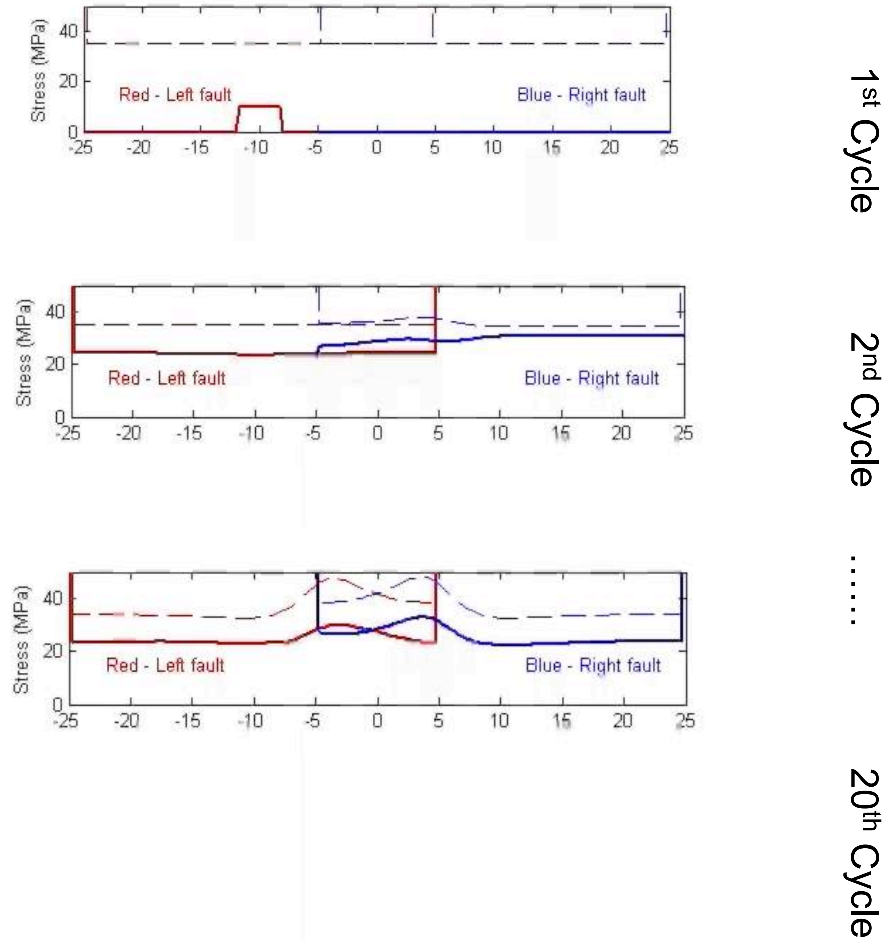
Duan and Oglesby (2005)



Stepover Faults

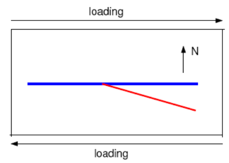
Dynamic rupture can jump across wider stepovers after a fault system experiences many earthquake cycles!



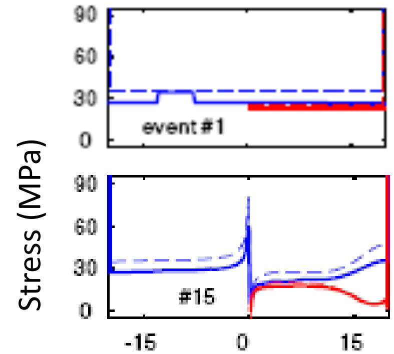


Duan and Oglesby (2006)

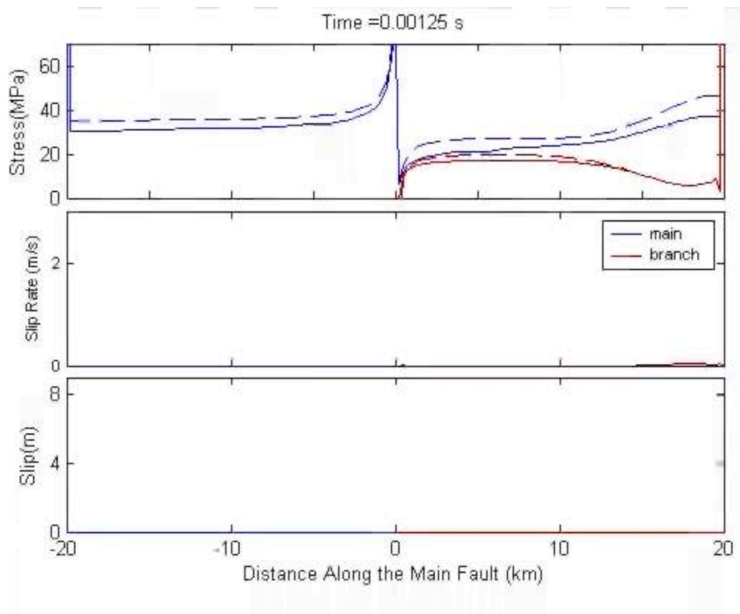
Branched Faults



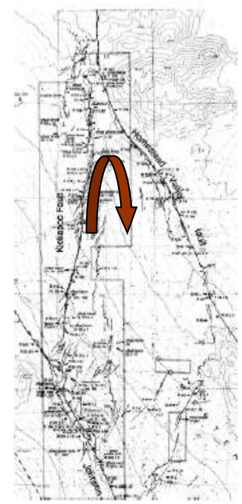
- Heterogeneous Initial stress
- Branching behavior in nonuniform prestress:
  - Different branching behaviors on a fault system;
  - Backward Branching in nonuniform stress field.



Distance Along Main-Fault Strike (km)

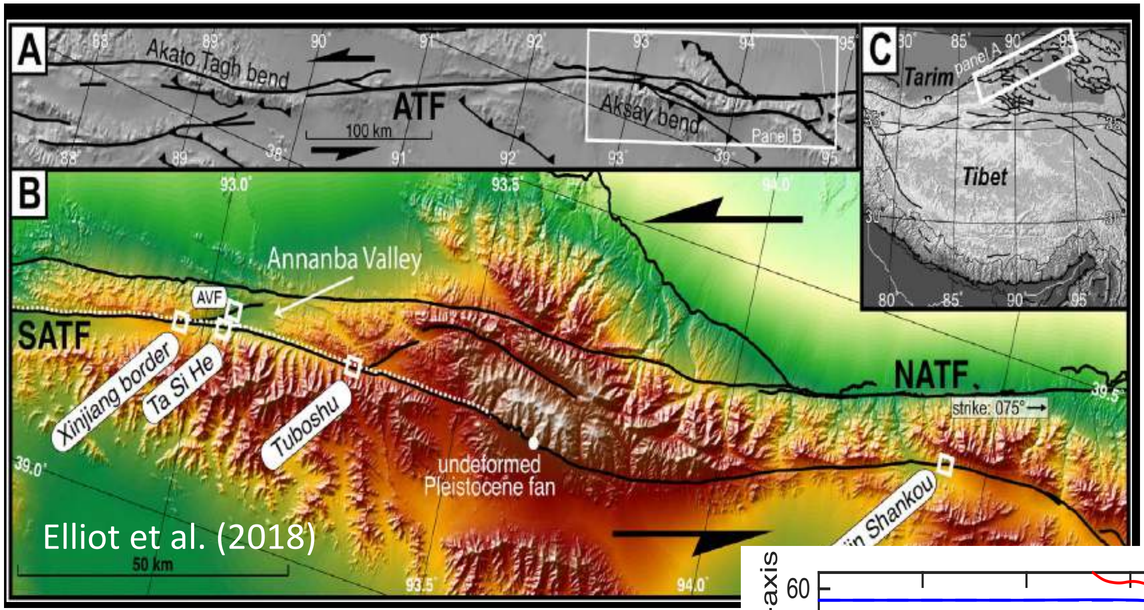


Duan and Oglesby (2007)

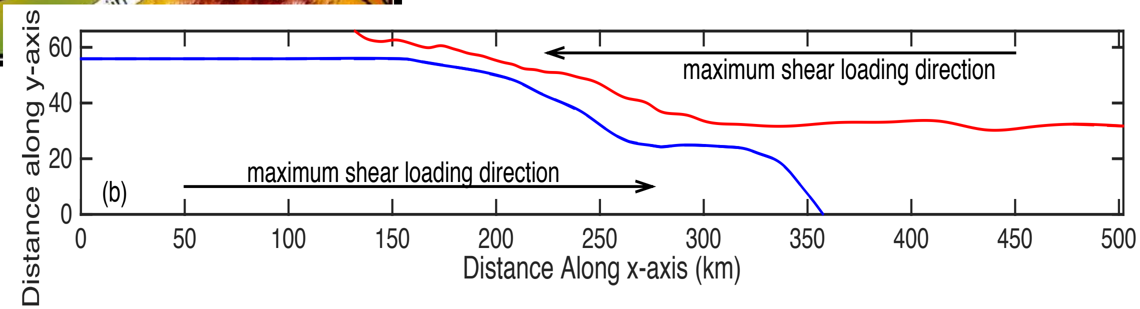


92 Landers,CA

2D Multicycle Dynamics of the Aksay Bend along the Altyn Tagh Fault: Duan et al. (2019)

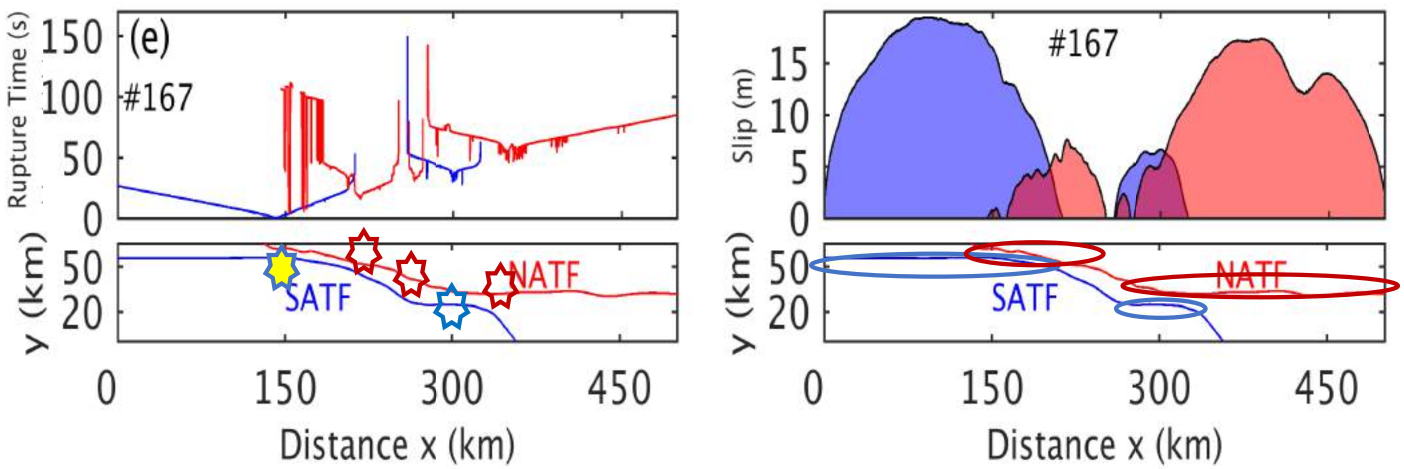


- Two active strands: SATF, NATF
- 200 km long, separated by > 5 km
- Restraining
- Mountains with peaks > 5.5 km



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

- One example:

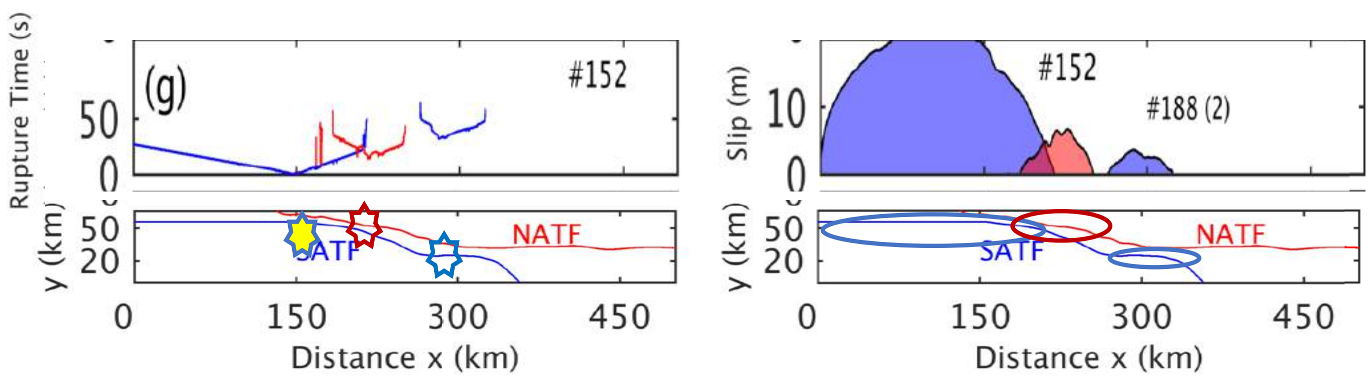


- **Ruptured most parts of the fault system: Jumping rupture - The EQ gate opens.**
- **Complex rupture propagation: triggering**

❖ Duan et al. (2019)

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

- Another example:



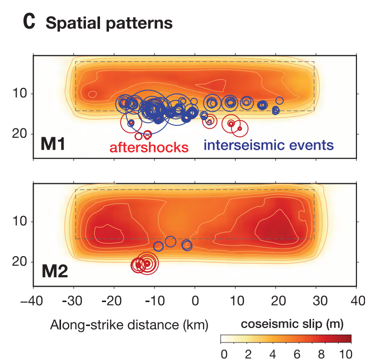
- **Ruptured one stem segment + some small portions within the bend: The EQ Gate is closed.**
- **Slip in one event on both strands may not necessarily suggest a giant, jumping event!**

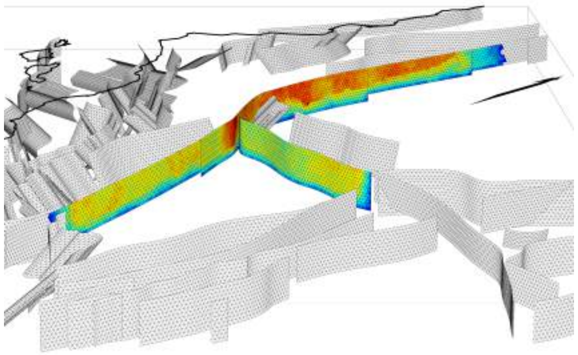
❖ Duan et al. (2019)

Existing 3D Earthquake Simulators in the Community

- Lapusta and co-worker: Boundary Integral
  - Fully dynamic for co-seismic rupture process
  - All other quasi-static phases: interseismic, nucleation, postseismic
  - **Limited to vertical strike-slip planar faults, uniform elastic media.**
- Dieterich at UC Riverside and co-worker: RSQSim
  - Boundary Element
  - **Not fully dynamic for co-seismic rupture process**
  - Applicable for complex faults, still uniform elastic media
  - Being used for CA hazard analysis: UCERF

Jiang and Lapusta (2016)

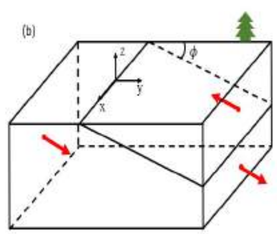


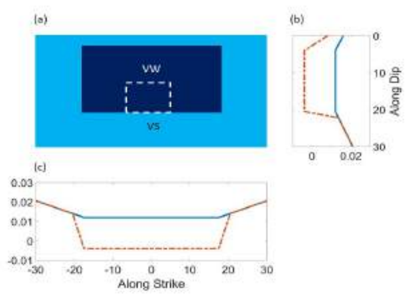


❖ Review: Existing Earthquake Simulators

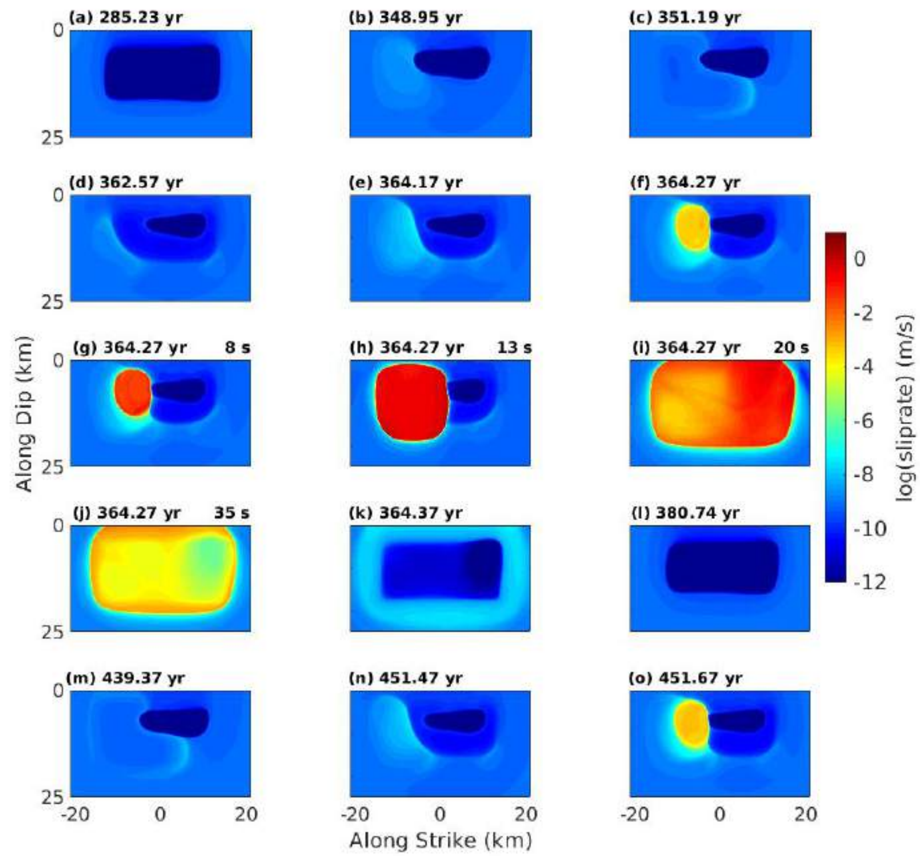
Developing 3D Dynamic Earthquake Simulators for Complex faults

- Features: fully capture co-seismic dynamic process on geometrically complex faults with rate-state friction.
- One effort: based on our dynamic FEM code EQdyna, using dynamic relaxation technique for quasi-static processes.



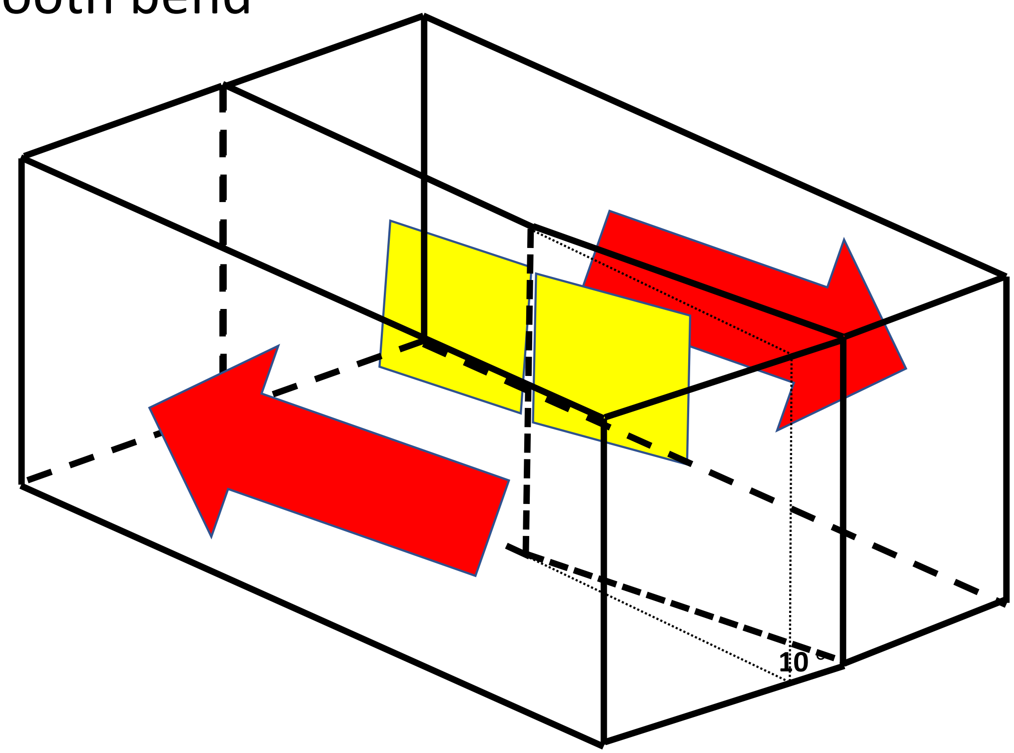


Luo et al. (2019, in revision)

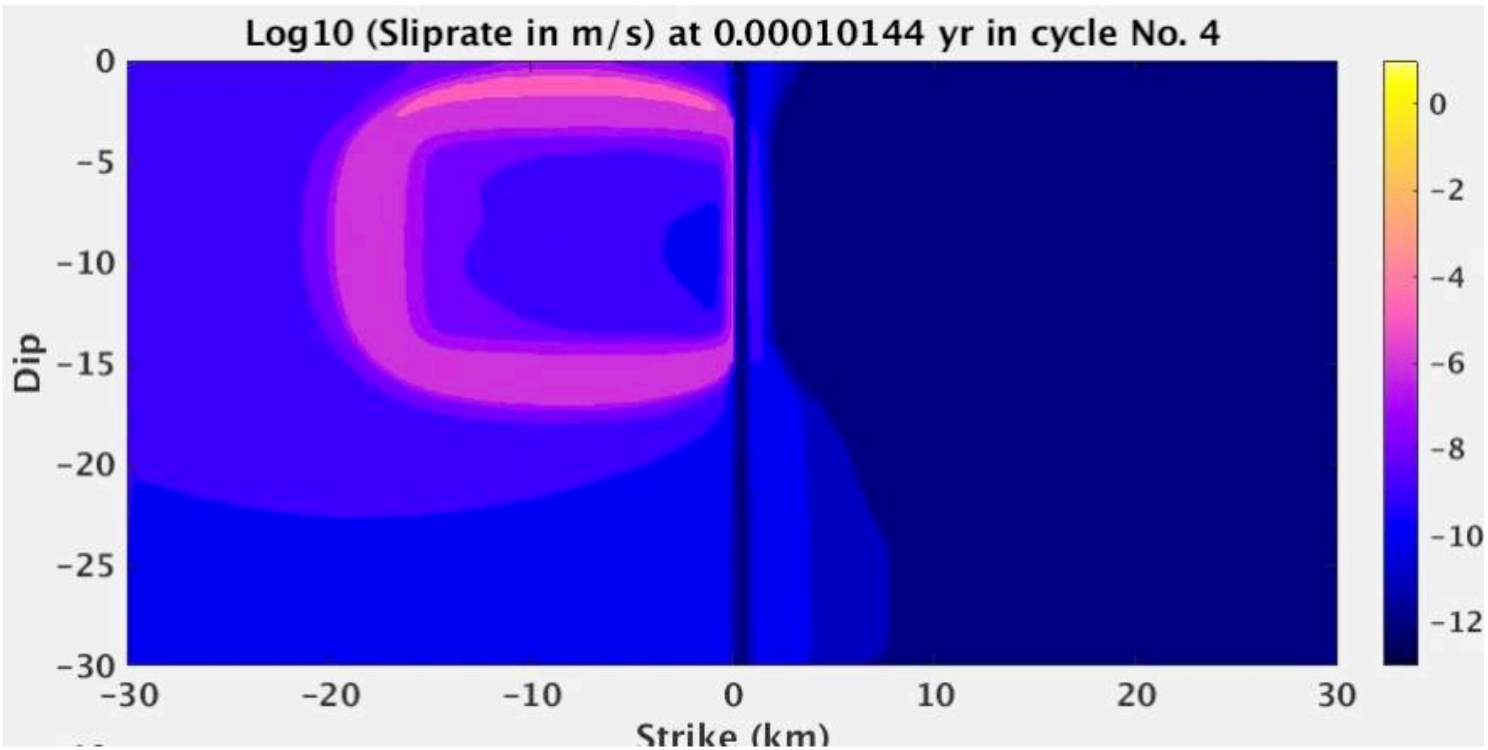


Developing dynamic EQ simulator (cont'd)

- Another effort: A newly developed quasi-static FEM code (EQquasi) + EQdyna (Liu et al., in preparation).
- Example: a 10° smooth bend



Earthquake cycles on the bent fault



Concluding Remarks

- **Fault stresses can be very heterogeneous** along geometrically complex faults over multiple earthquake cycles, and these heterogeneous stresses play **a critical role in dynamic rupture propagation**.

- **Multicycle dynamic models (Dynamic earthquake simulators)** provide a means to track heterogeneous fault stresses and thus explore different rupture behaviors along a given fault system: address earthquake gate problems.

- **Will these heterogeneous stresses be characterized in CSM?**
  - If yes, how?
  - Integration of geodynamic models, long-term tectonic models, and short-term dynamic rupture models and various observations may be a way to go.

- **More interactions between CSM and dynamic rupture groups** may be needed.