Rupture Propagation on Branching Faults

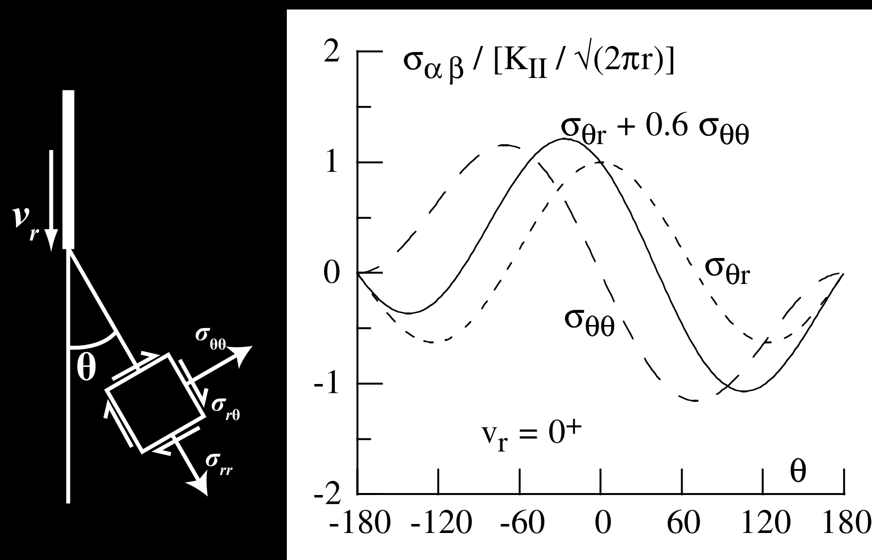
2009 SCEC Rupture Dynamics Code Validation Workshop

Nora DeDontney

Outline

- Branching theory and discussion of significant parameters
- Modeling of recent branched rupture earthquakes
- Recent work with Finite Element Modeling
- Branch formation and quantifying existing fault geometries

Stresses Around a Propagating Rupture



(Poliakov et al., JGR 2002)

- The stress distribution is highly dependent on the rupture velocity.
- As the rupture speed increases, the peak shear stress moves off of the plane of the main fault.
- The coulomb stress is asymmetric, resulting in favorable branch nucleation on the extensional side of the fault.

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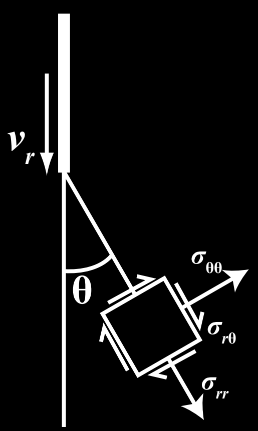

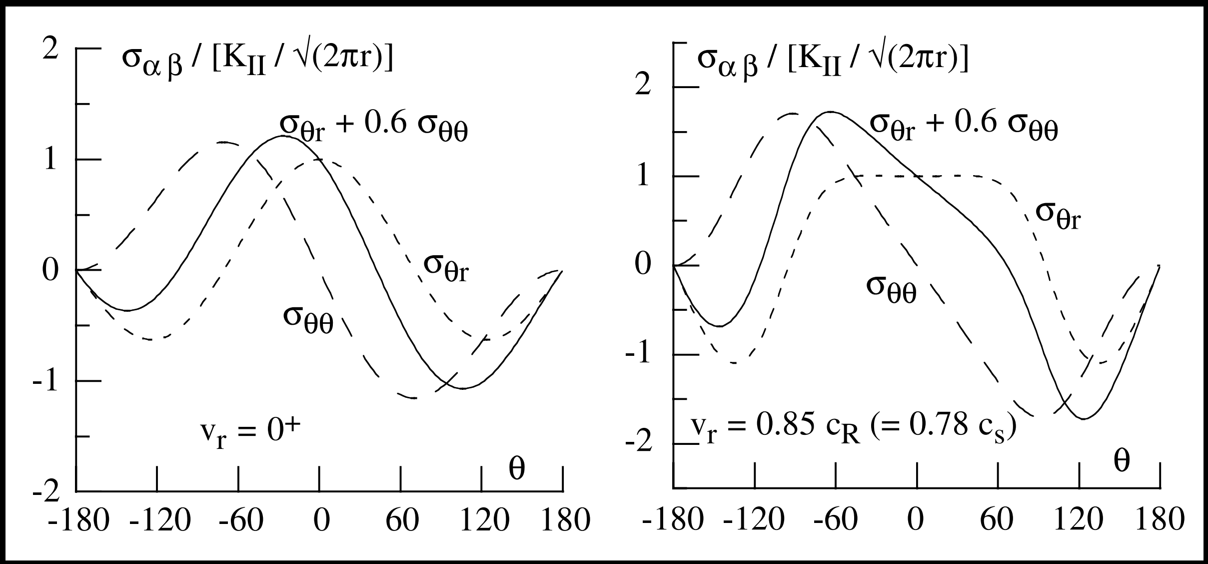

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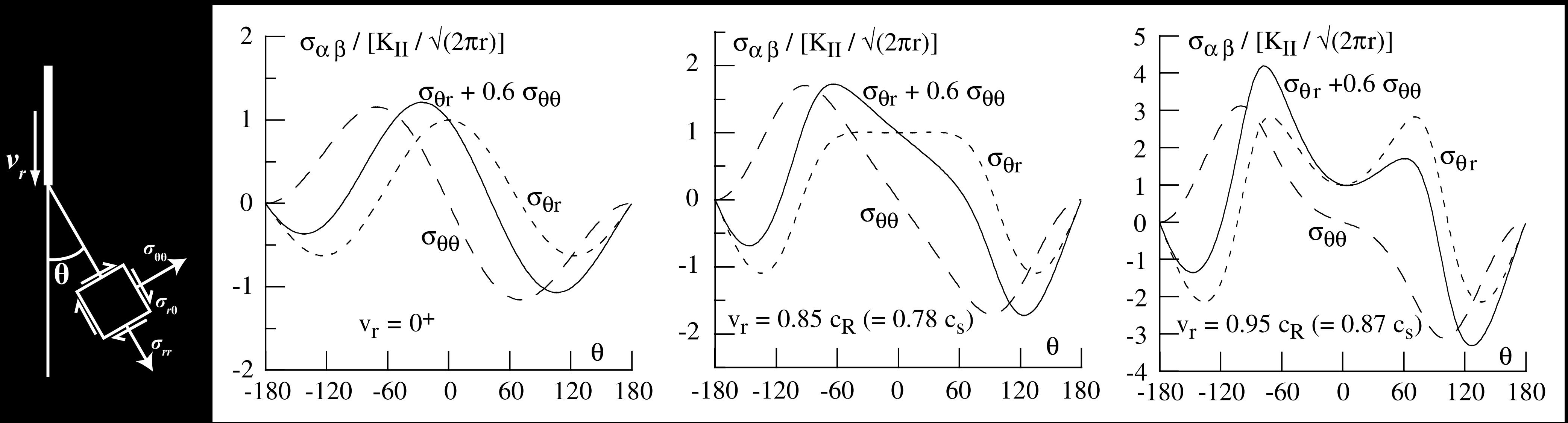

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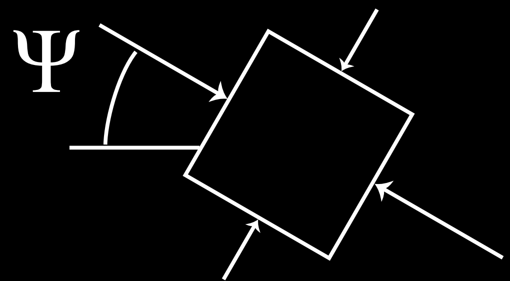
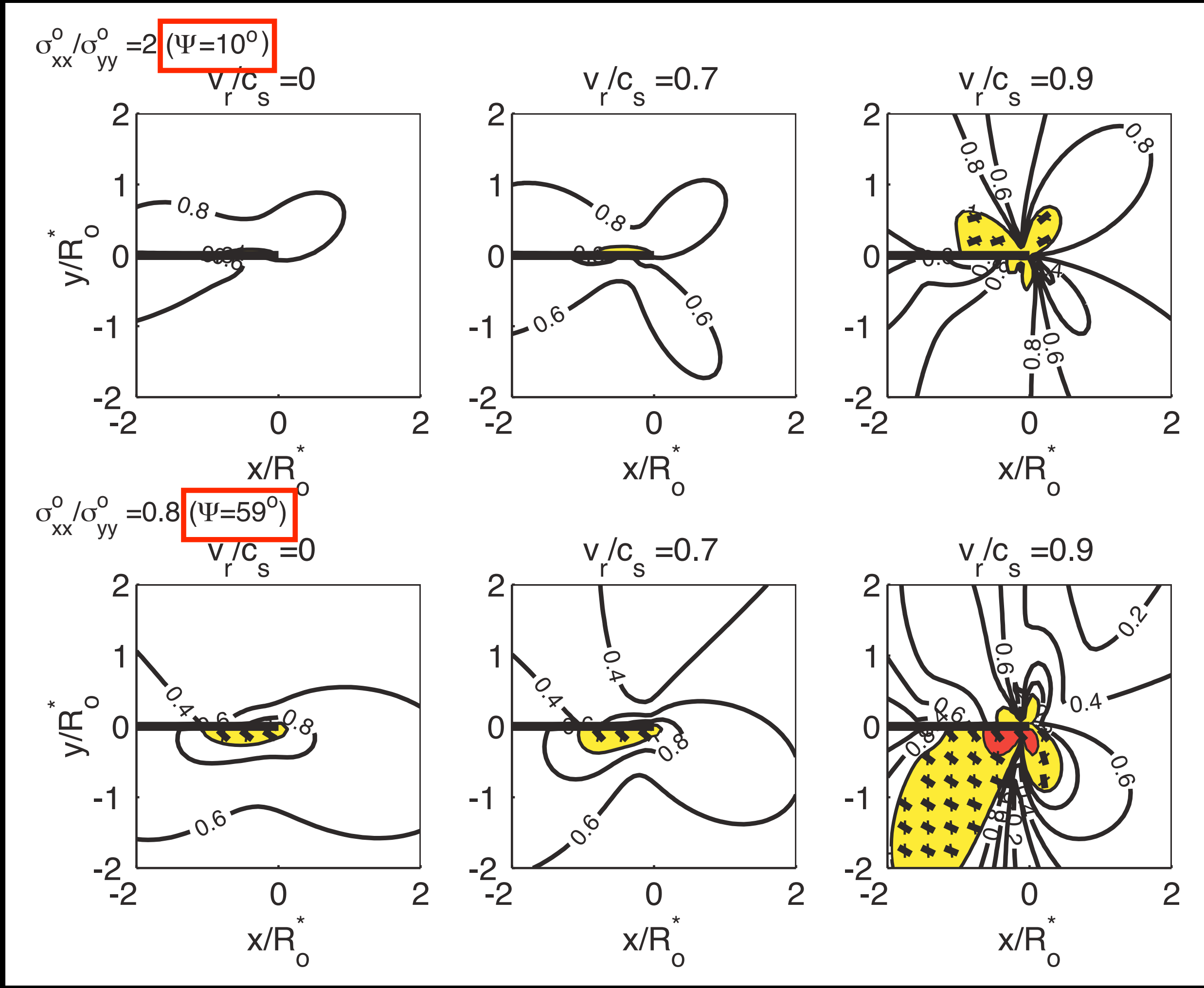
Off Fault Failure



Yellow: Shear Failure
Red: Tensile Failure

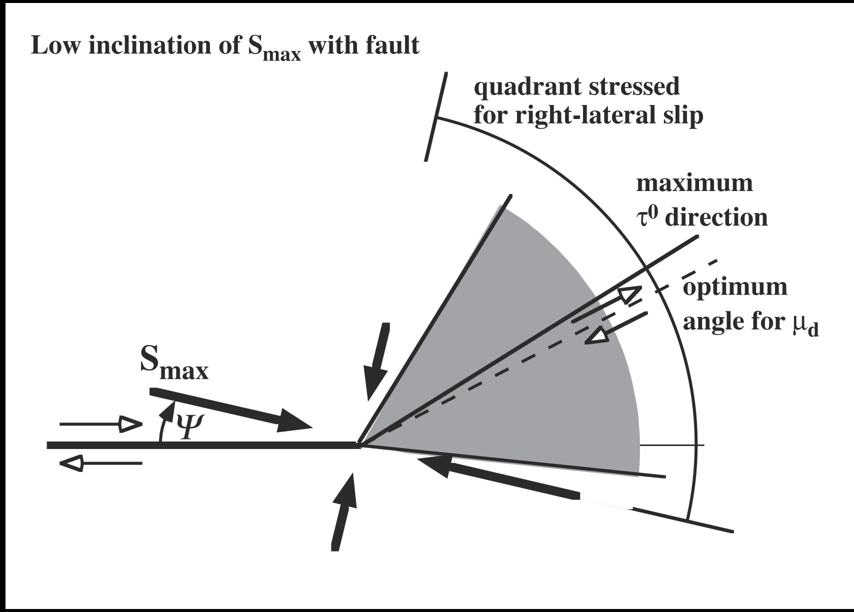


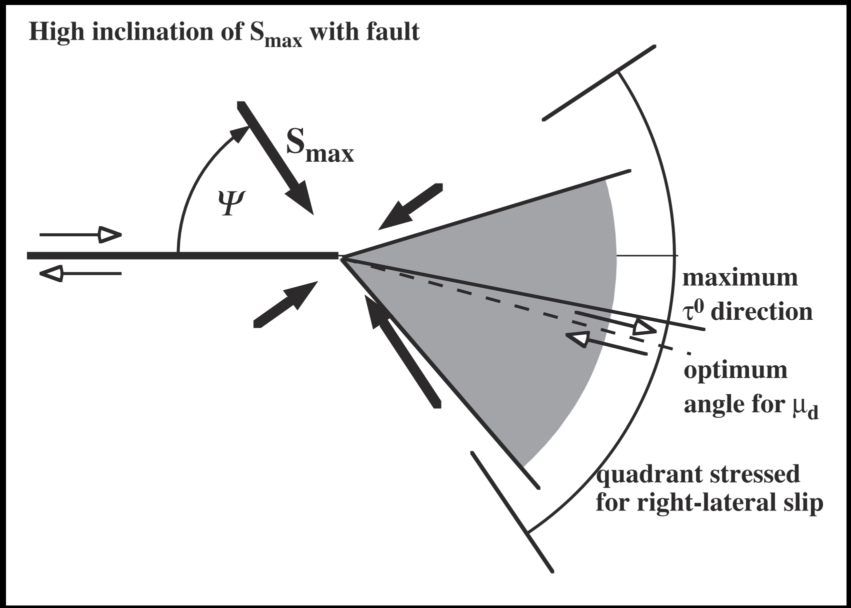
- The stresses at the propagating crack tip predict Mohr-Coulomb failure in the medium
- The zone of deformation changes with rupture speed and Ψ

(Poliakov et al., JGR 2002)

Large Scale Stress Field

- While the stresses at the rupture tip control the nucleation of rupture on a branch, the background stress field identifies the regions in which rupture continuation is favorable.
- The angle between the most compressive stress and the main fault, Ψ, characterizes this effect.

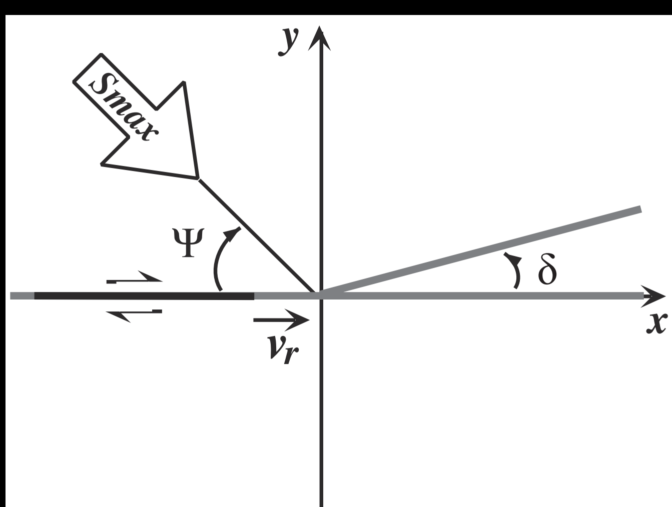


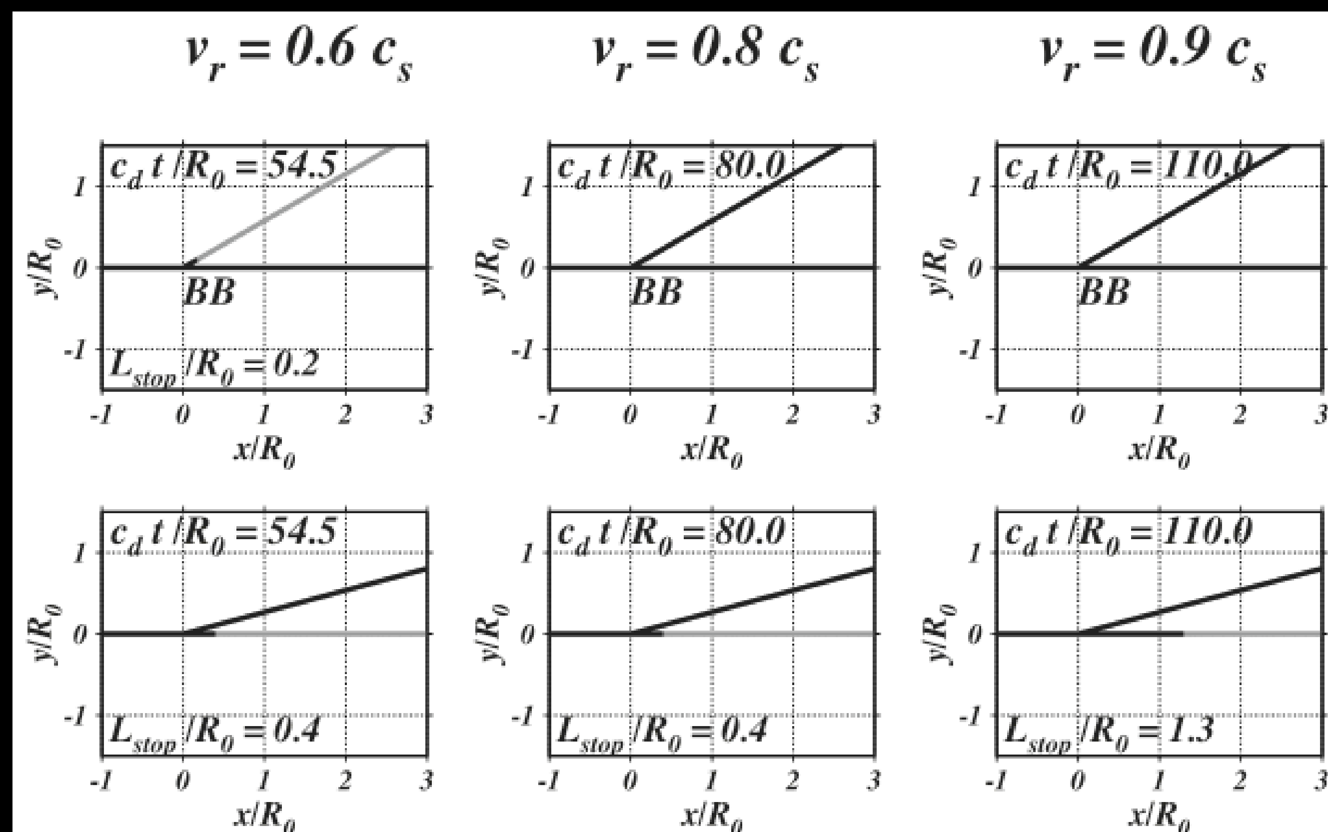


(Kame et al., JGR 2003)

Prestress and Rupture Velocity Effects

- The side of the main fault that is favored for branching is determined by the prestress state.
- Dynamic effects alter the rupture path selection





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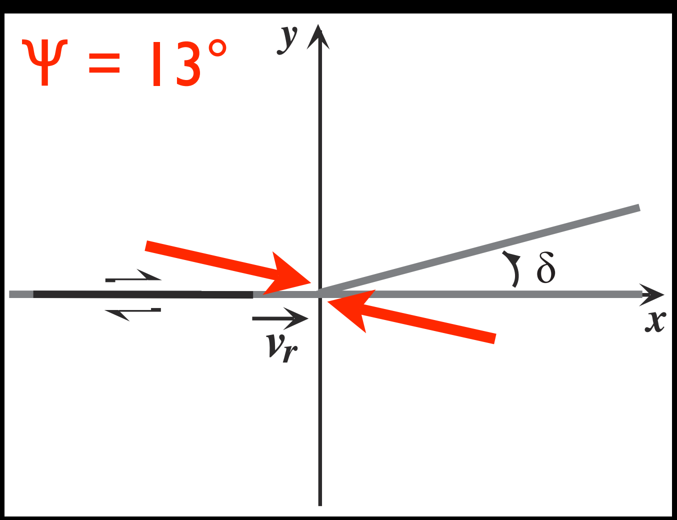

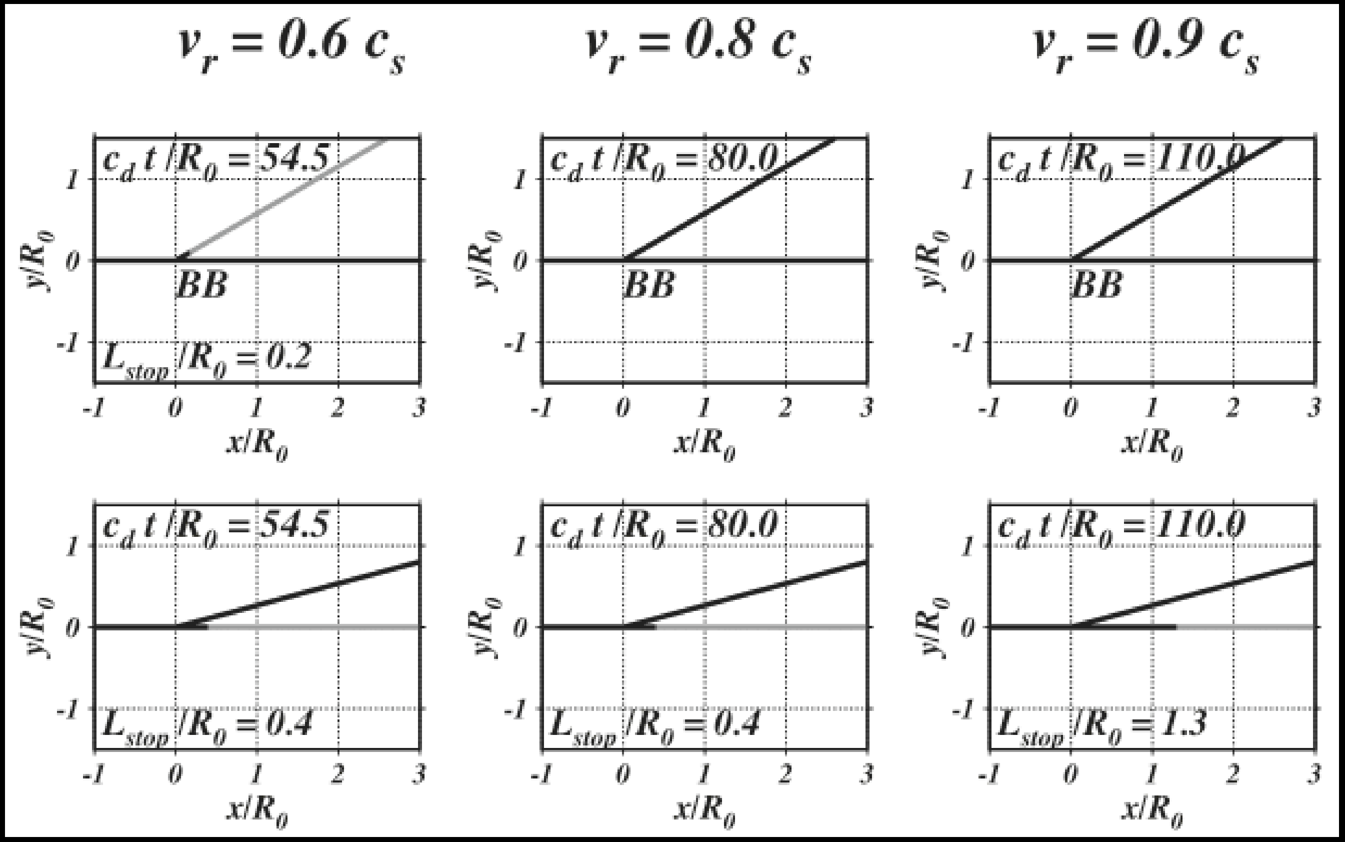

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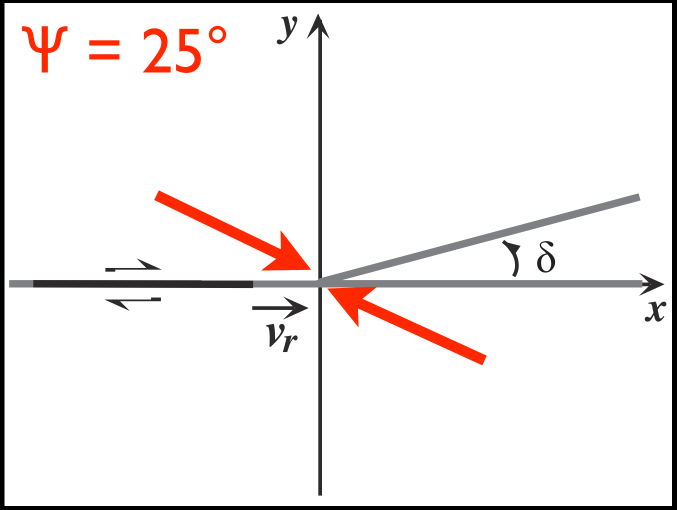

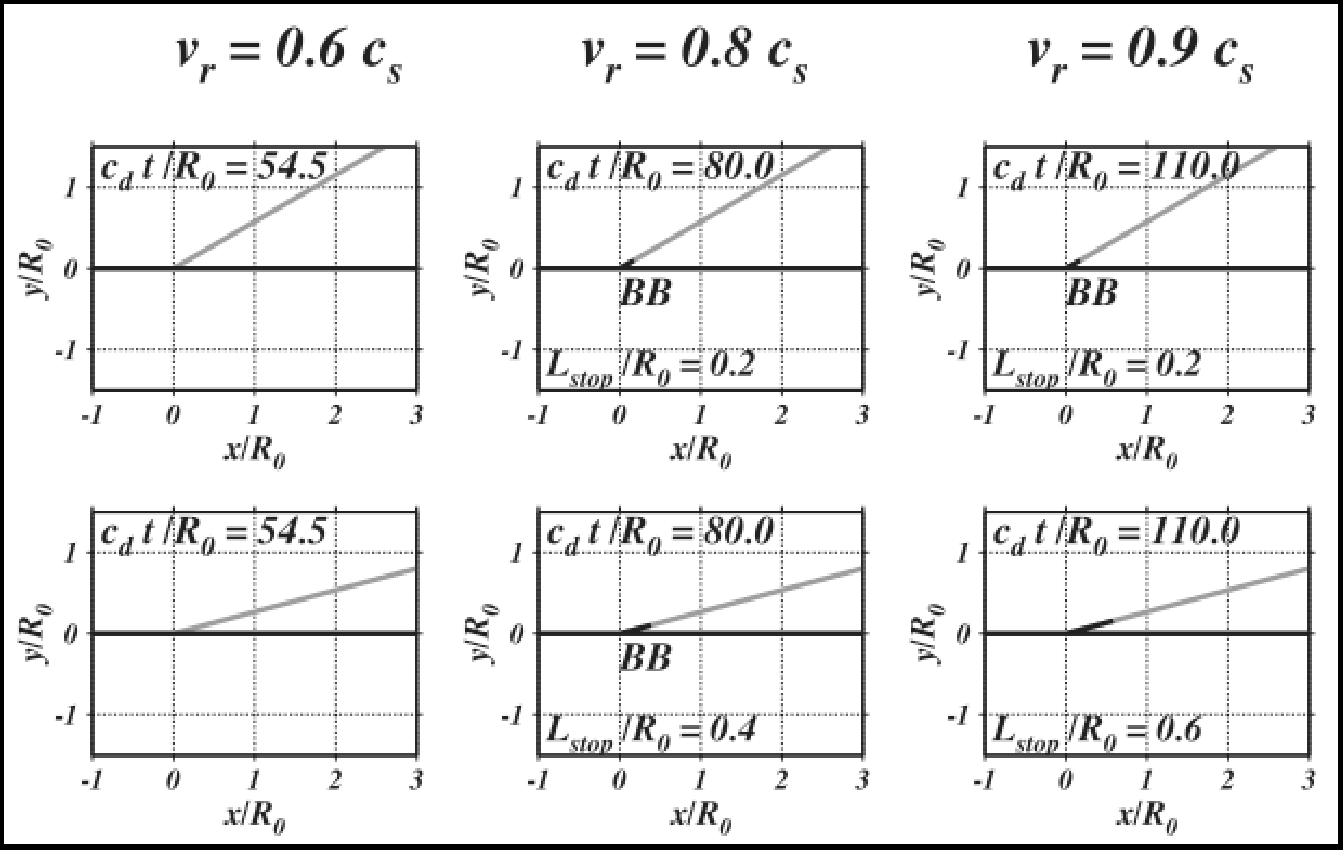

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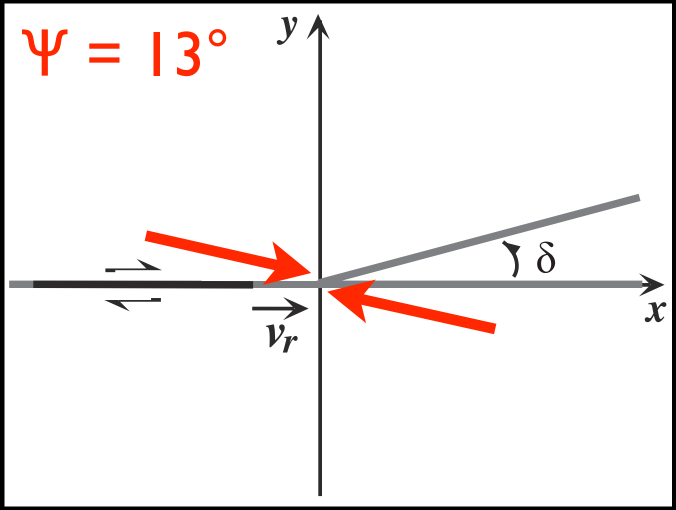

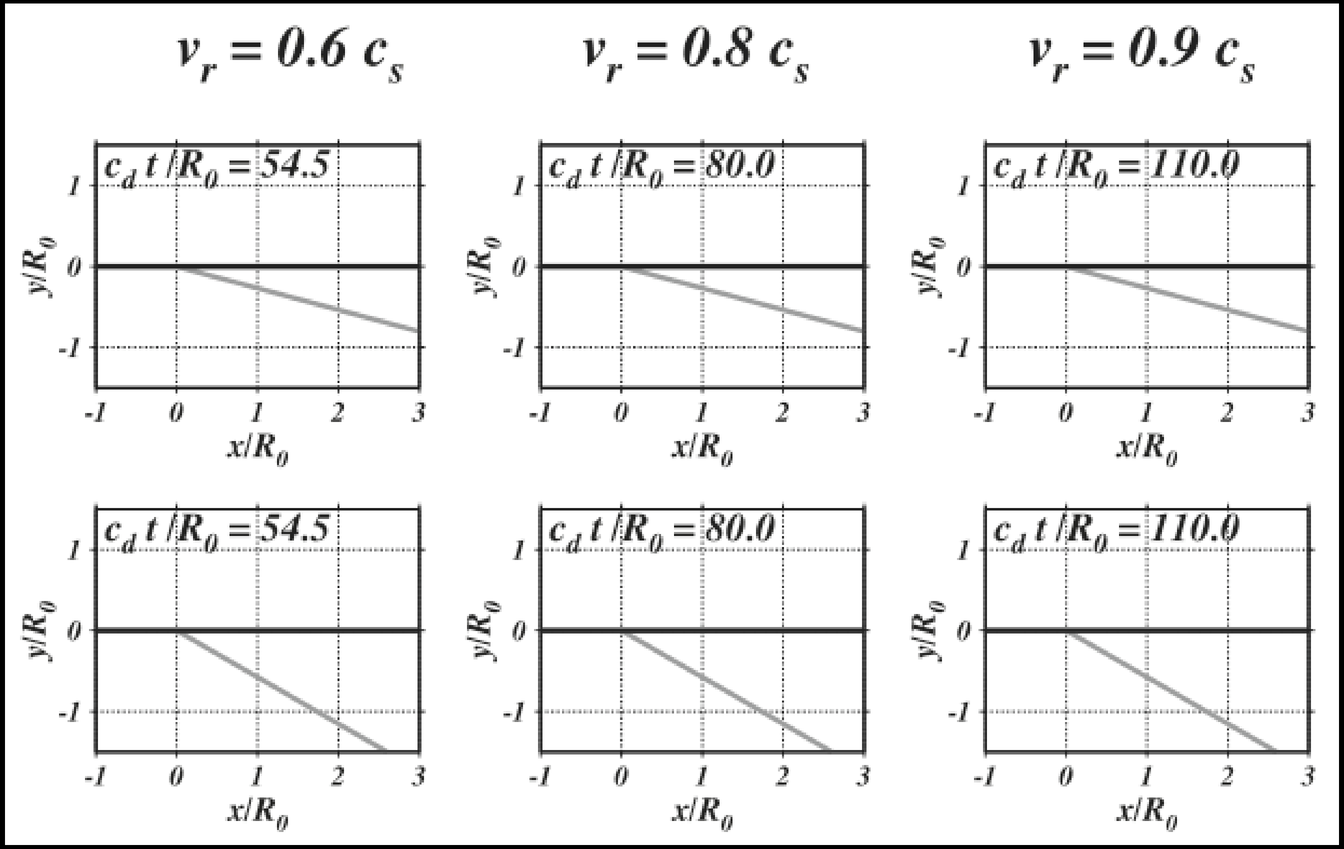

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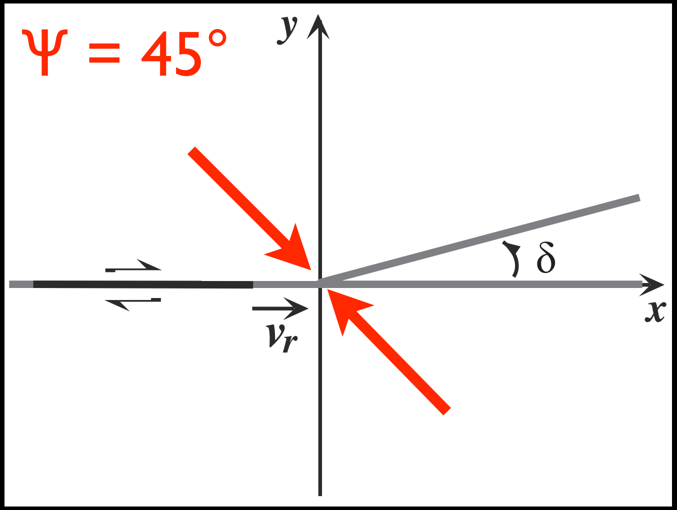

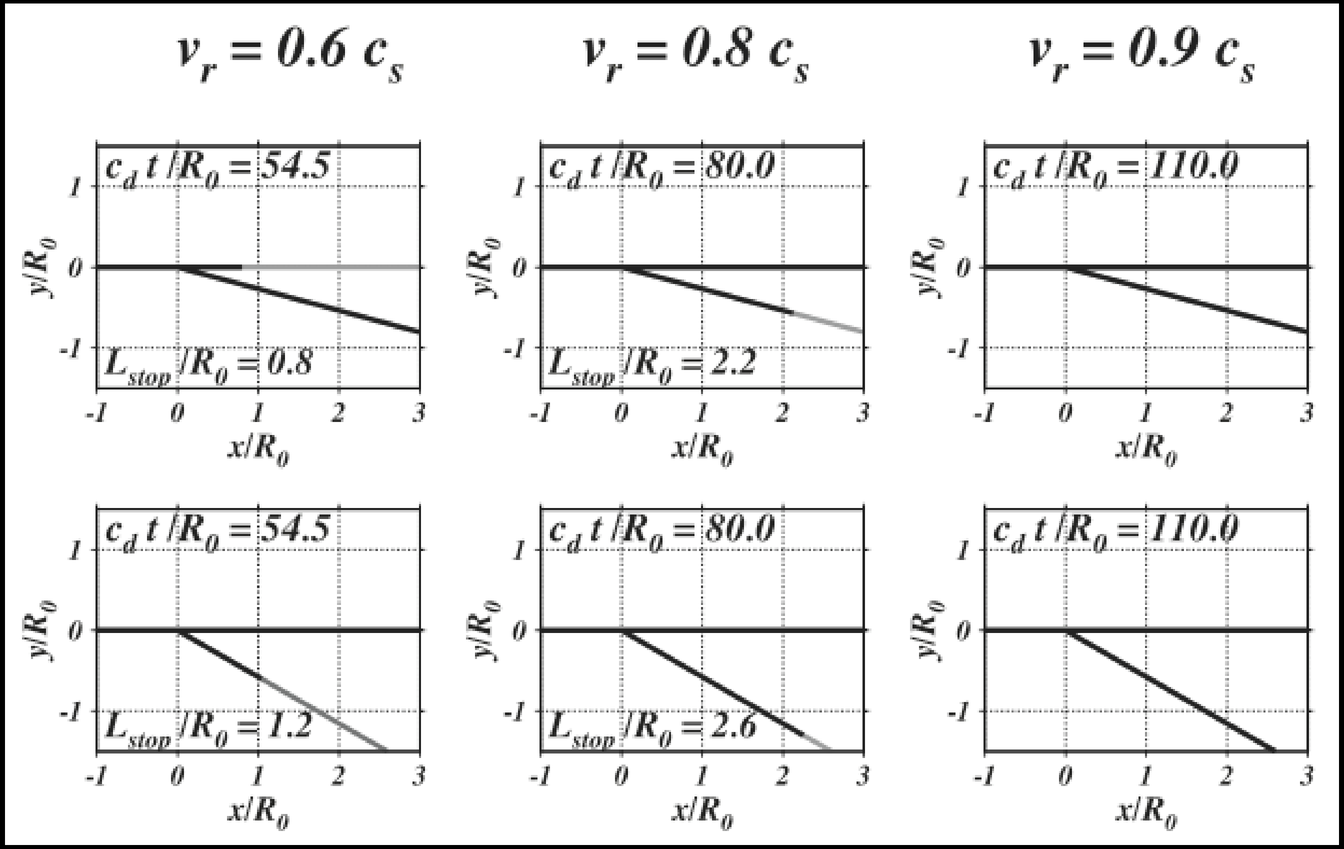

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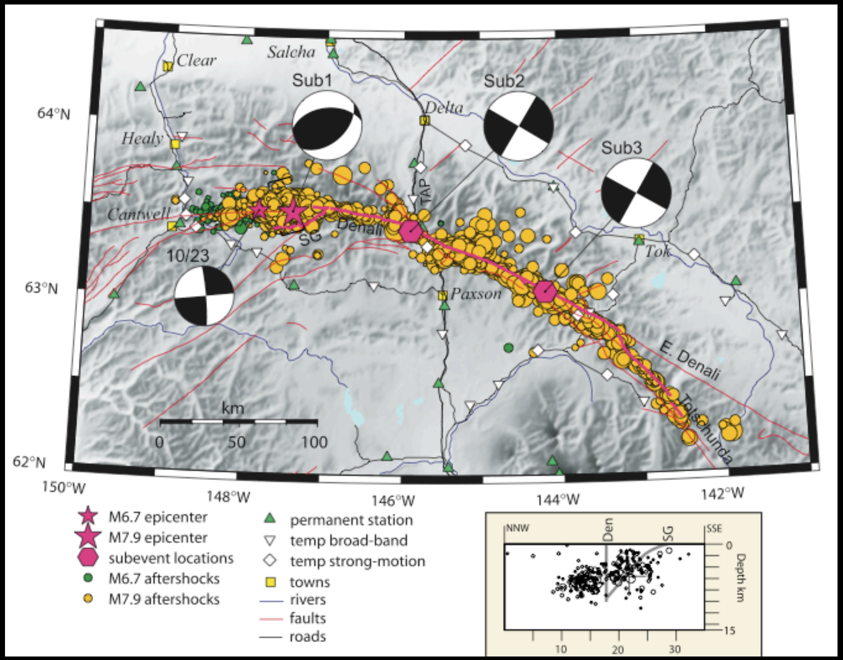
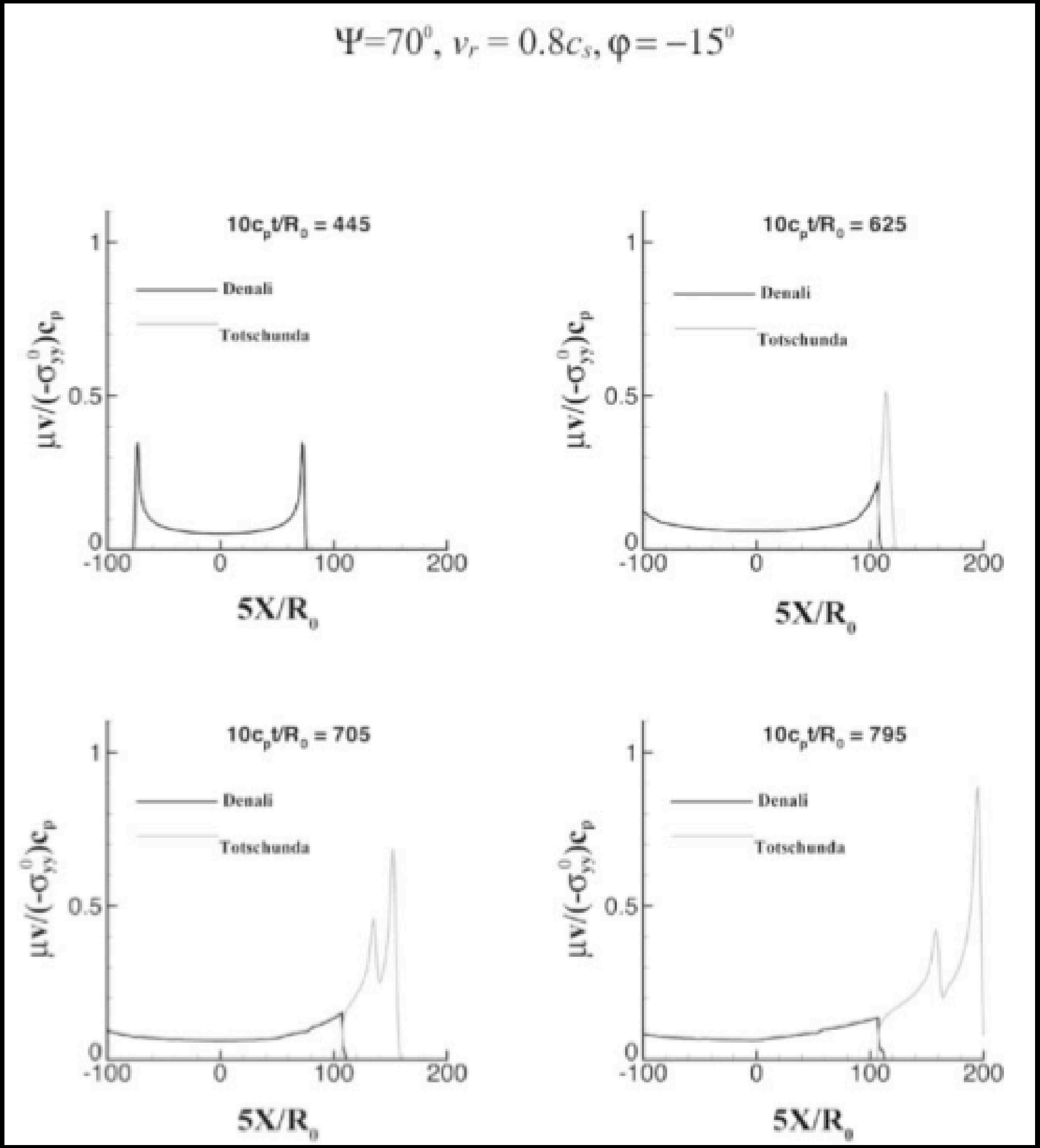
- Branching theory and discussion of significant parameters
  - Rupture velocity
  - Principal stress orientation
  - Branch Geometry
- Modeling of recent branched rupture earthquakes
- Recent work with Finite Element Modeling
- Branch formation and quantifying existing fault geometries

2002, Mw 7.9, Denali



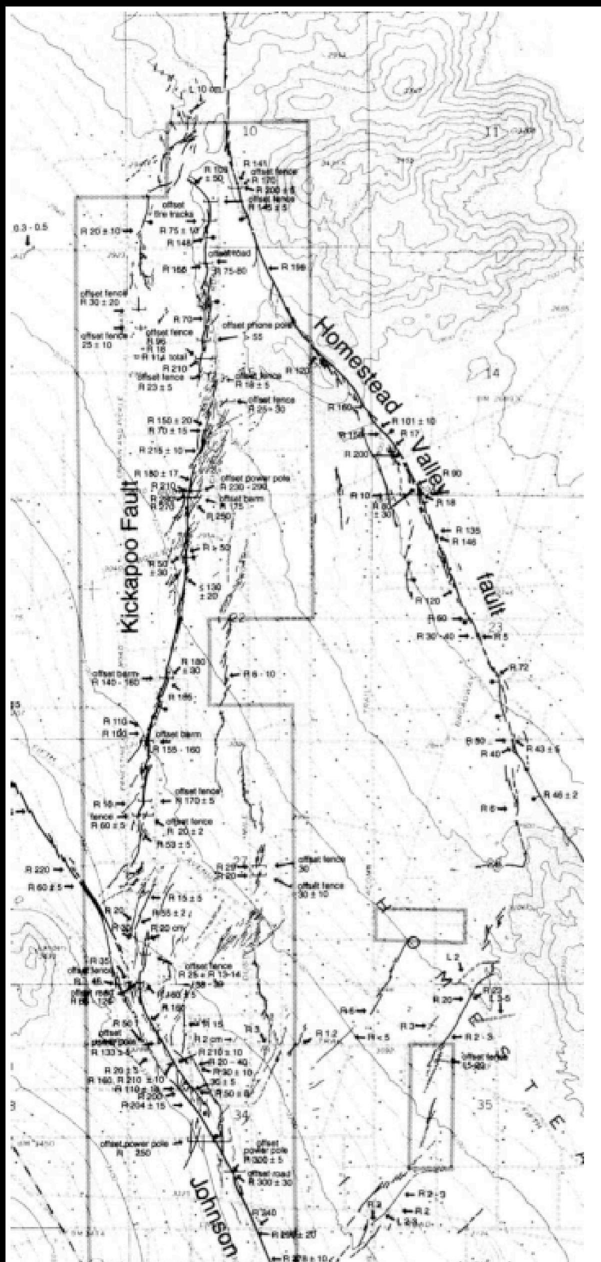
(Eberhart-Phillips et al., Science 2003)

- Modeled using the Boundary Integral Equation Method
- Using a variety of rupture velocities and stress orientations, the Totschunda branch fault is preferentially chosen

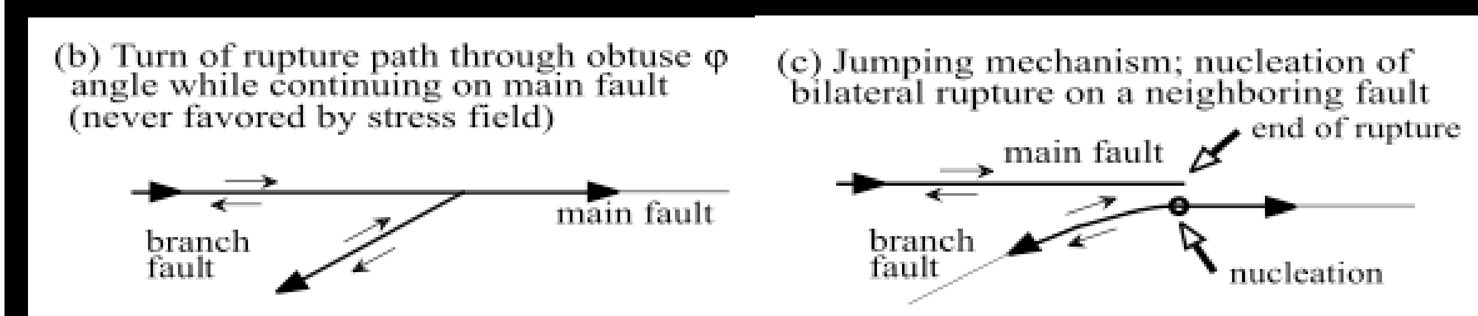


(Bhat et al., BSSA 2004)

Backwards Branching



- The 1992 Landers event is a good case study for a variety of rupture behaviors.
- For continuous faults at the branch intersection, branching is not favored by the stress field.
- Termination of rupture on the main fault can lead to a jumping of the rupture to a nearby fault, making it difficult to use the fault geometry to determine previous rupture directivity.



(Fliss et al., JGR 2005)

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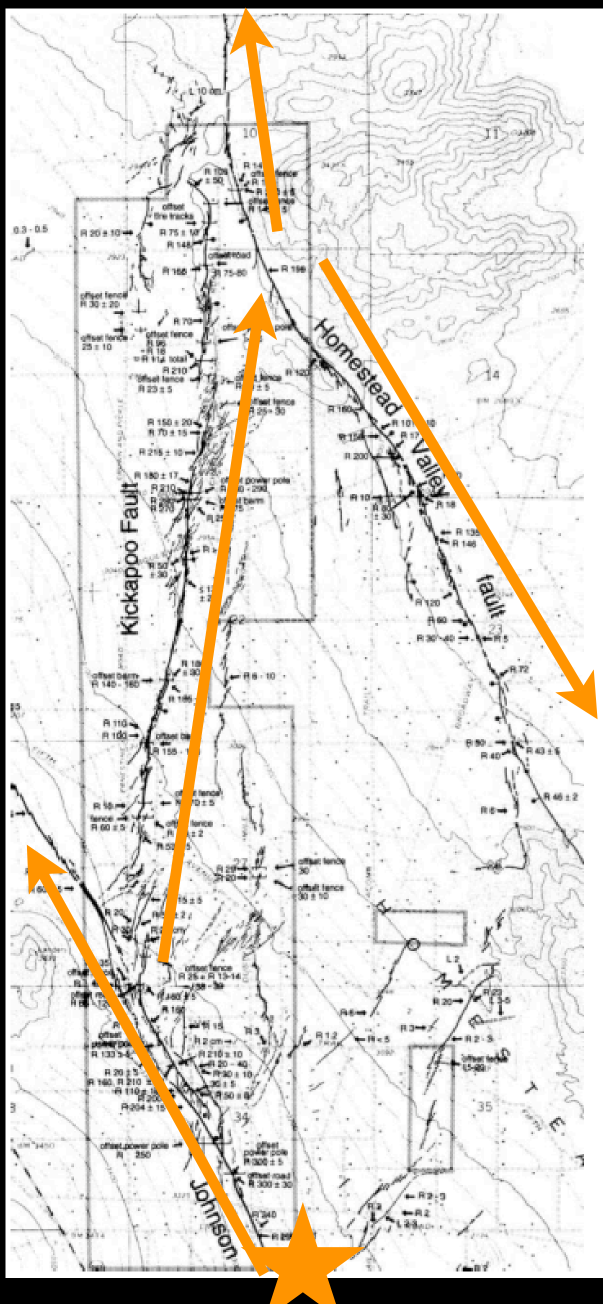

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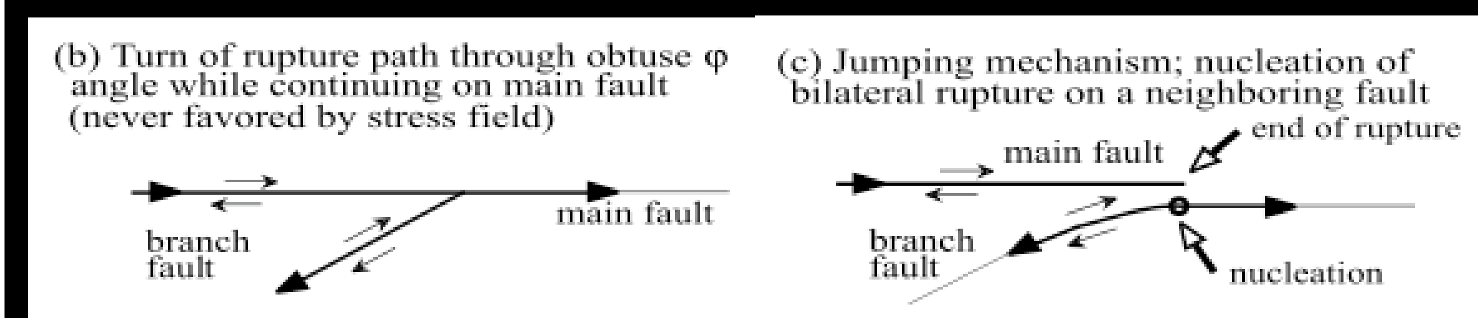

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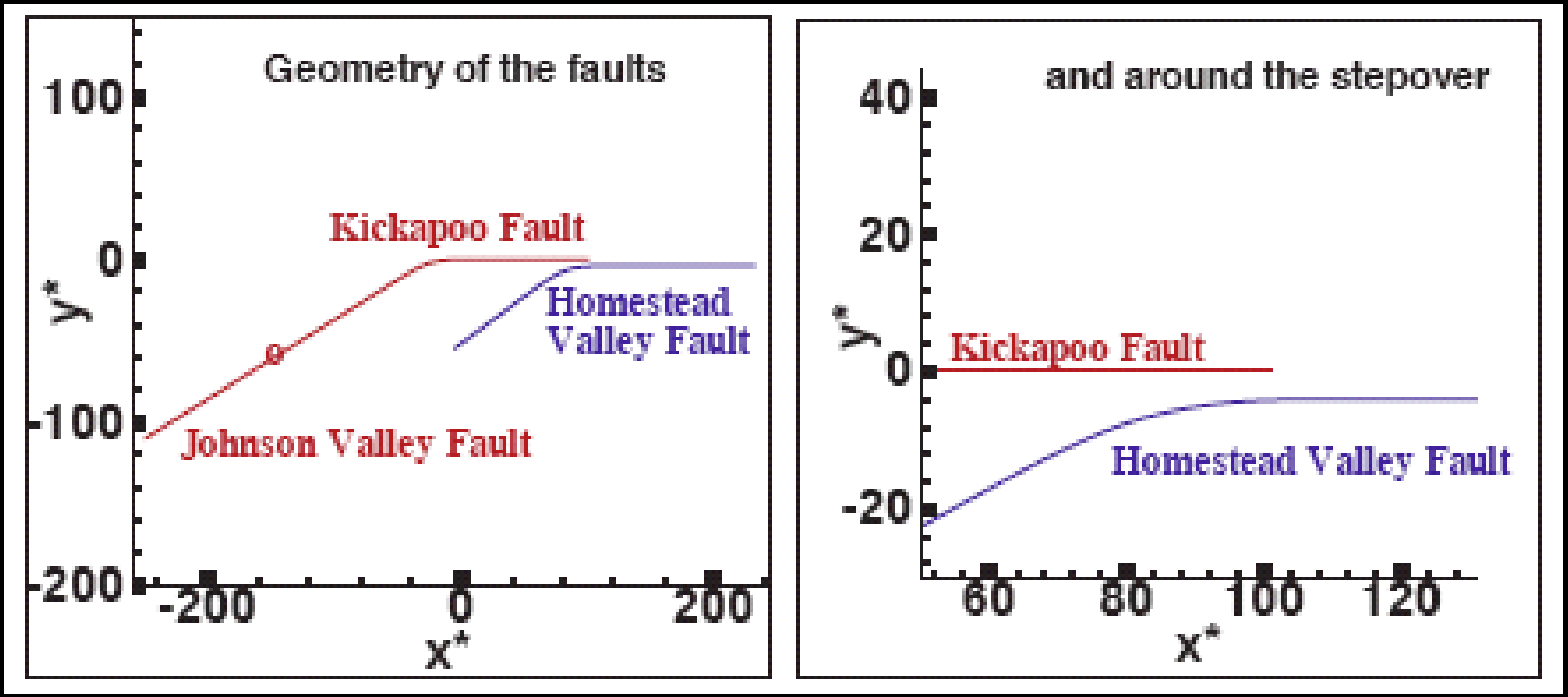
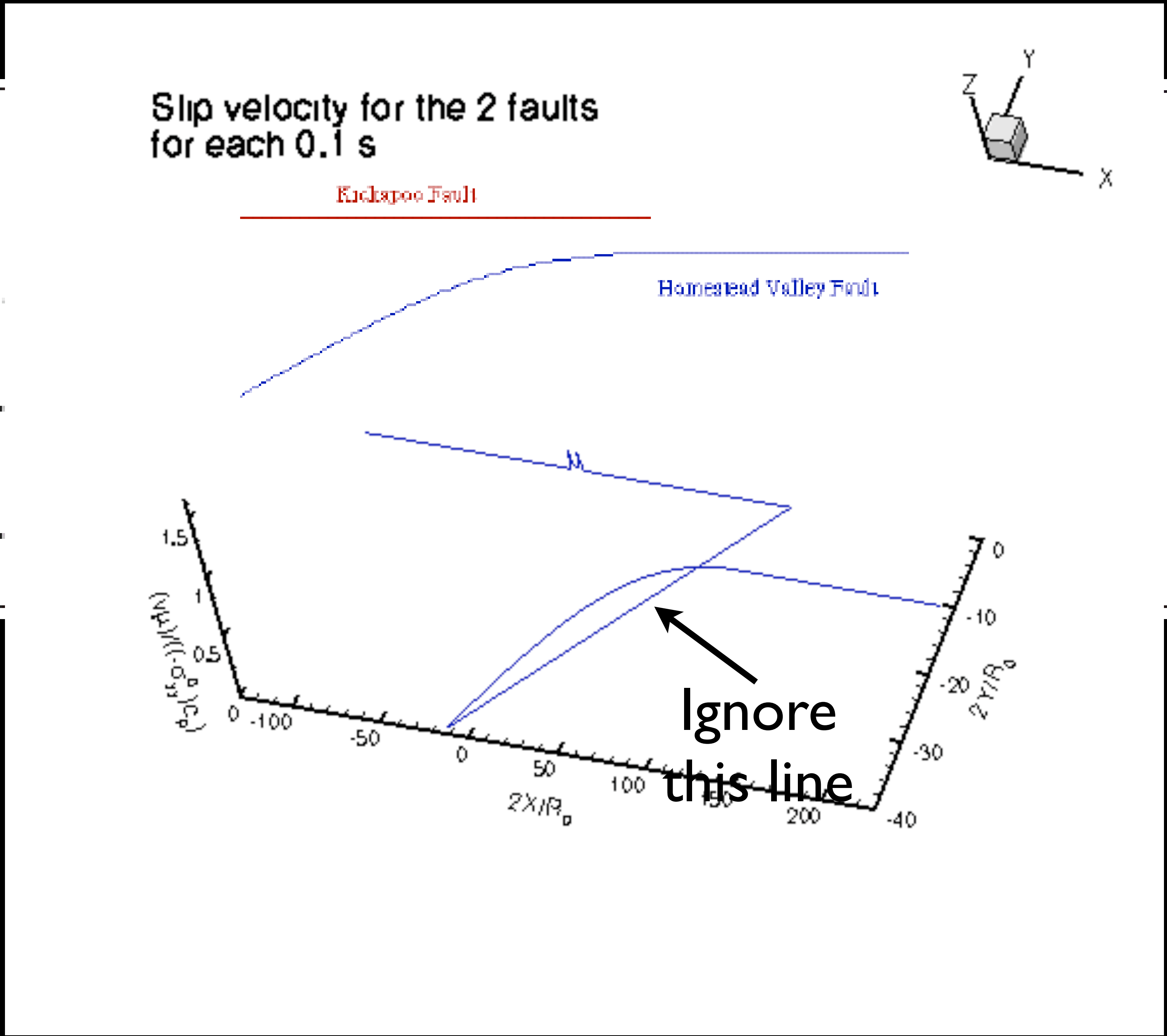


- Two separate faults are modeled using the Boundary Integral Equation Method

Backwards Branching



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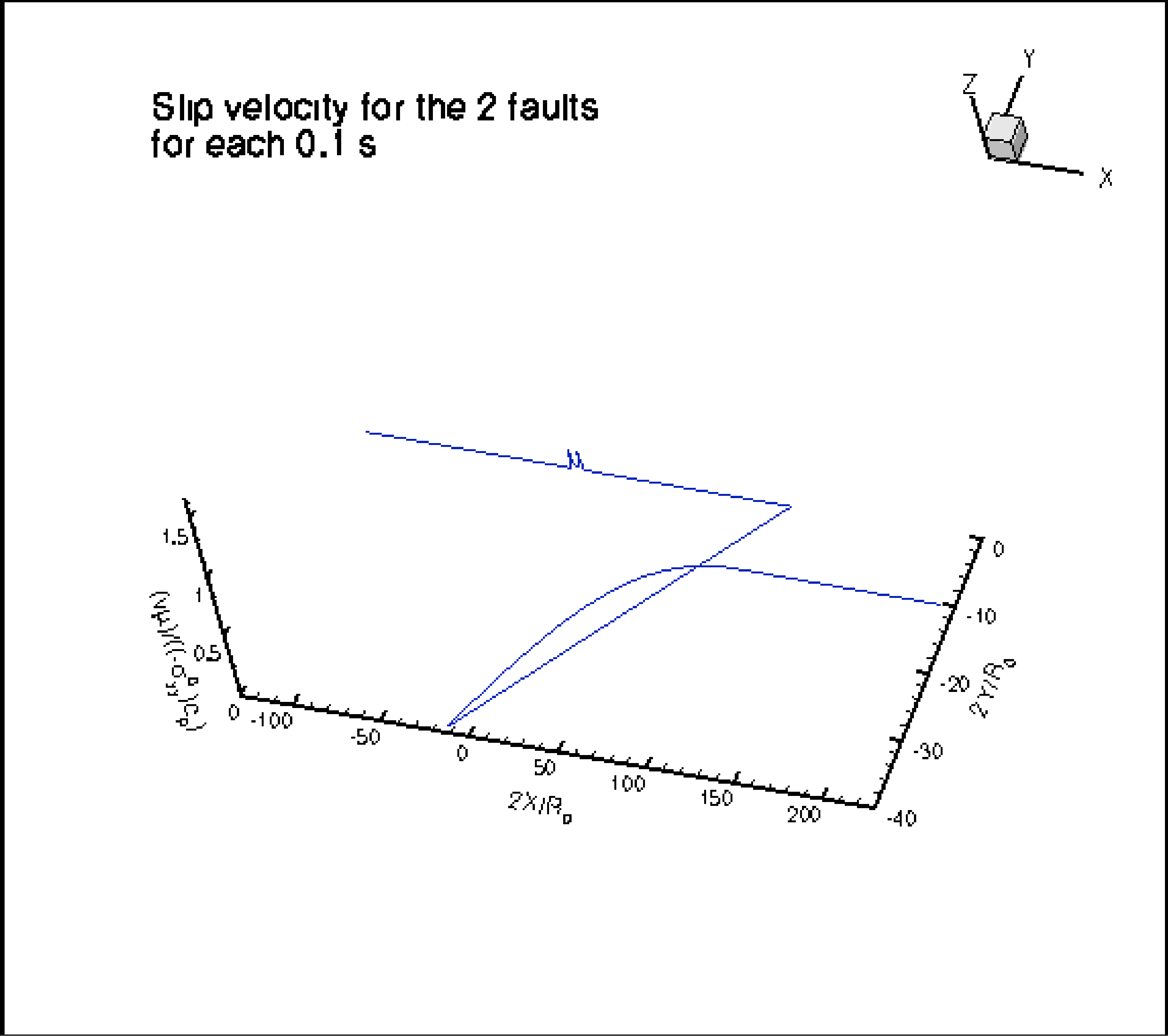
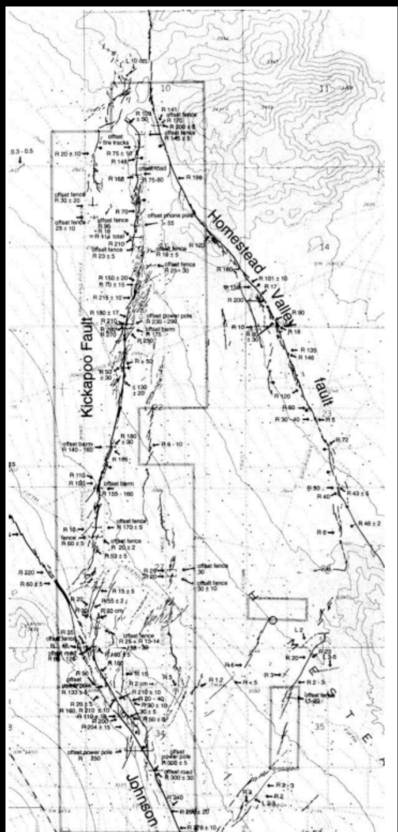


Finite Branches



- Small branches exist and rupture during major events, so how does this effect the rupture propagation along the main fault?
- When rupture stops along the branch fault, the radiated stresses affect the rupture on the main fault.
- Branches on the compressional side have little effect on the main fault propagation, but branches on the extensional side can influence the rupture.

(Bhat et al., JGR 2007)

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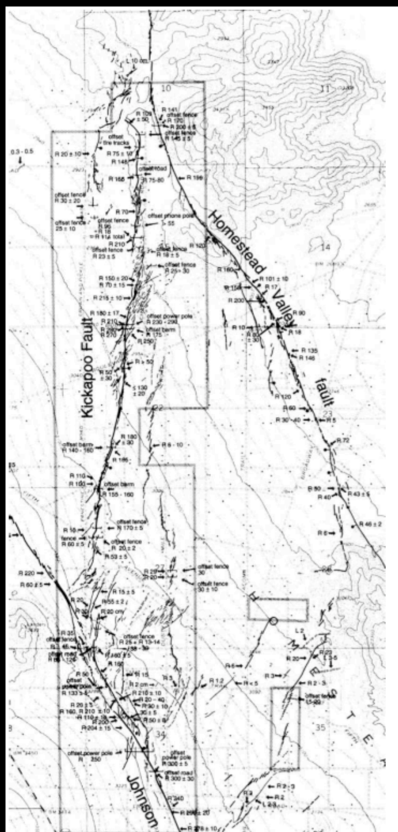

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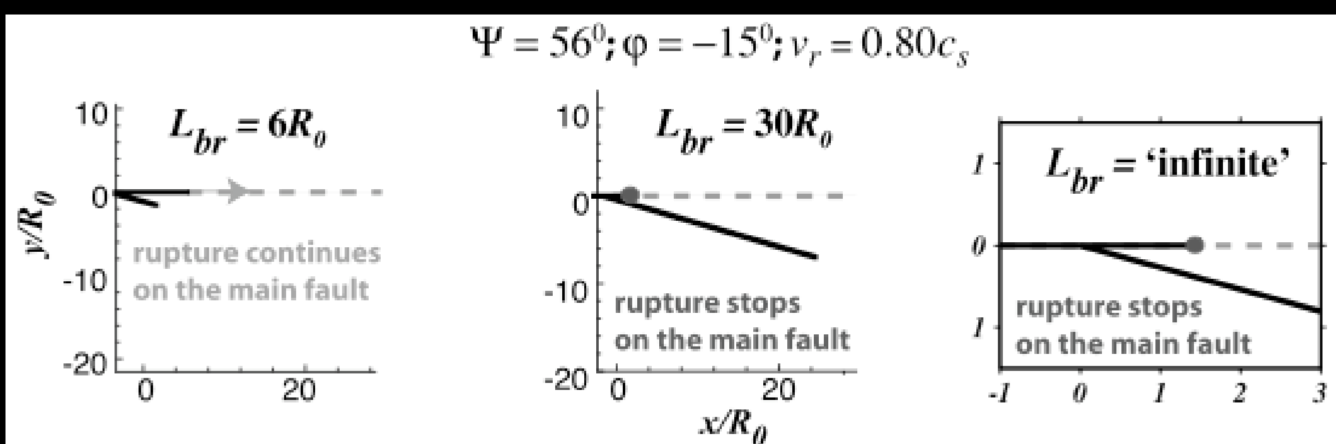

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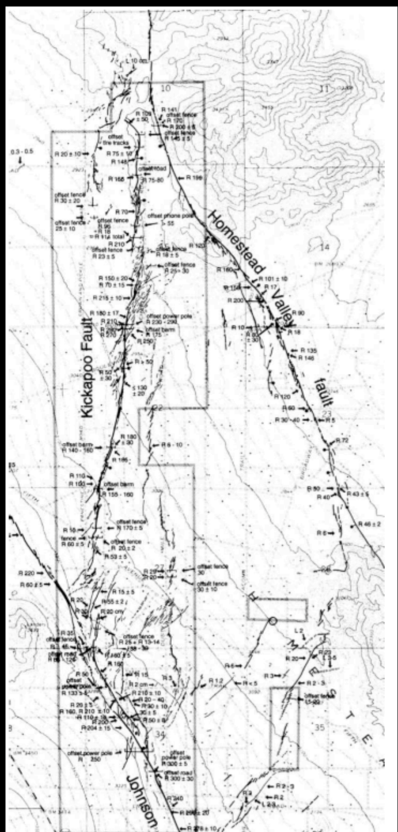
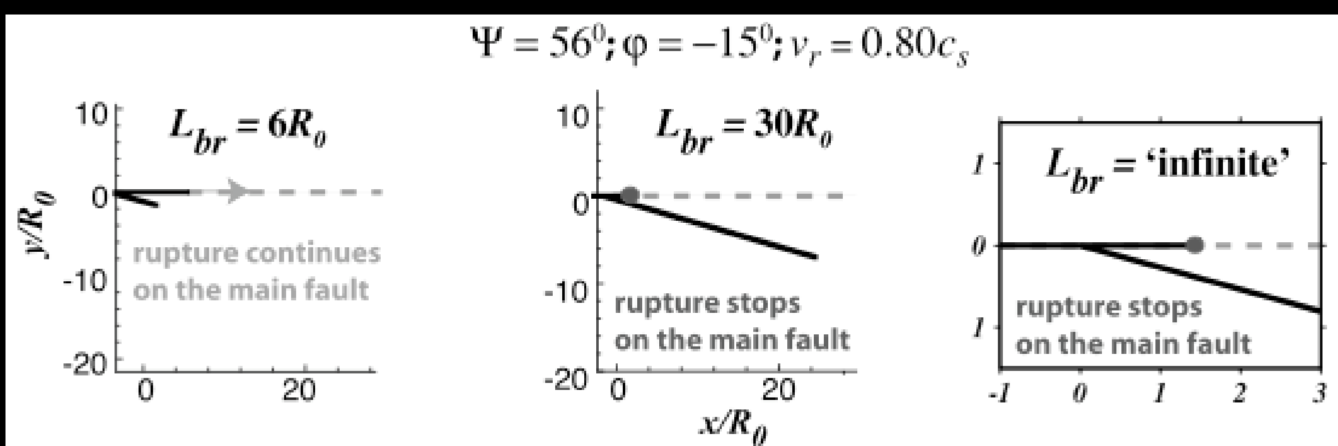
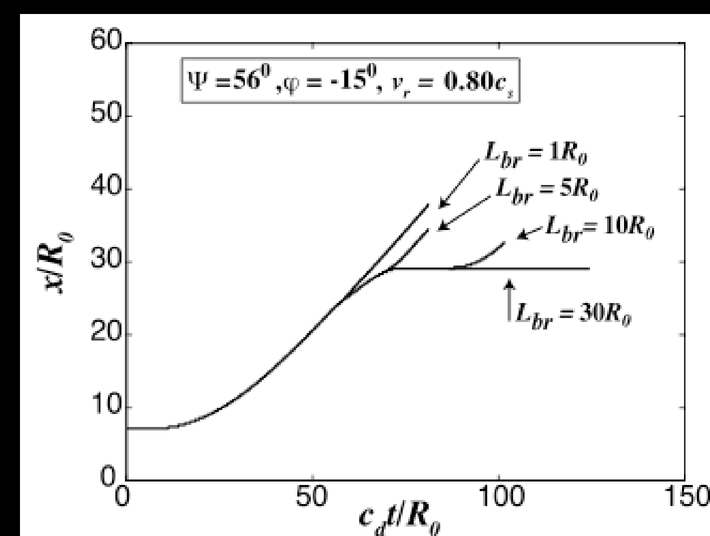


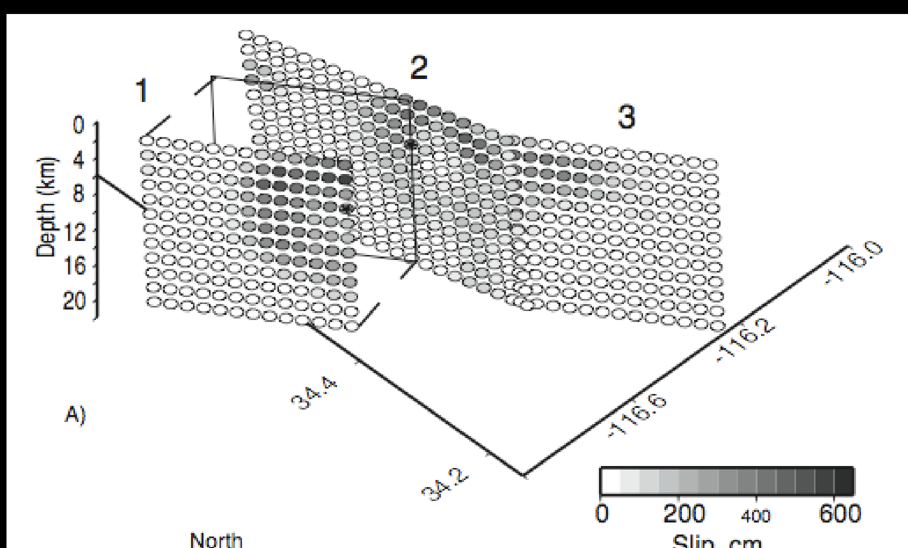




(Bhat et al., JGR 2007)

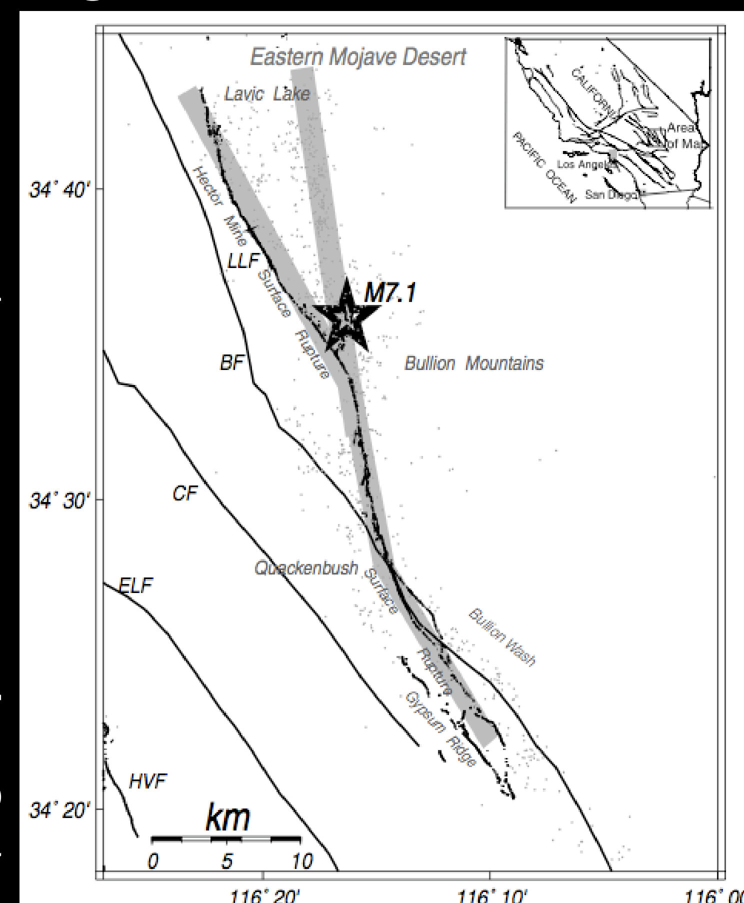
1999 Mw 7.1, Hector Mine

- Although the Lavic Lake fault did not rupture the surface, seismic and geodetic inversions show significant slip on this segment.
- 3D modeling shows that when the Lavic Lake near surface is prevented from rupturing, the near surface region of the northwest branch is brought closer to failure, which allows both branches to rupture.



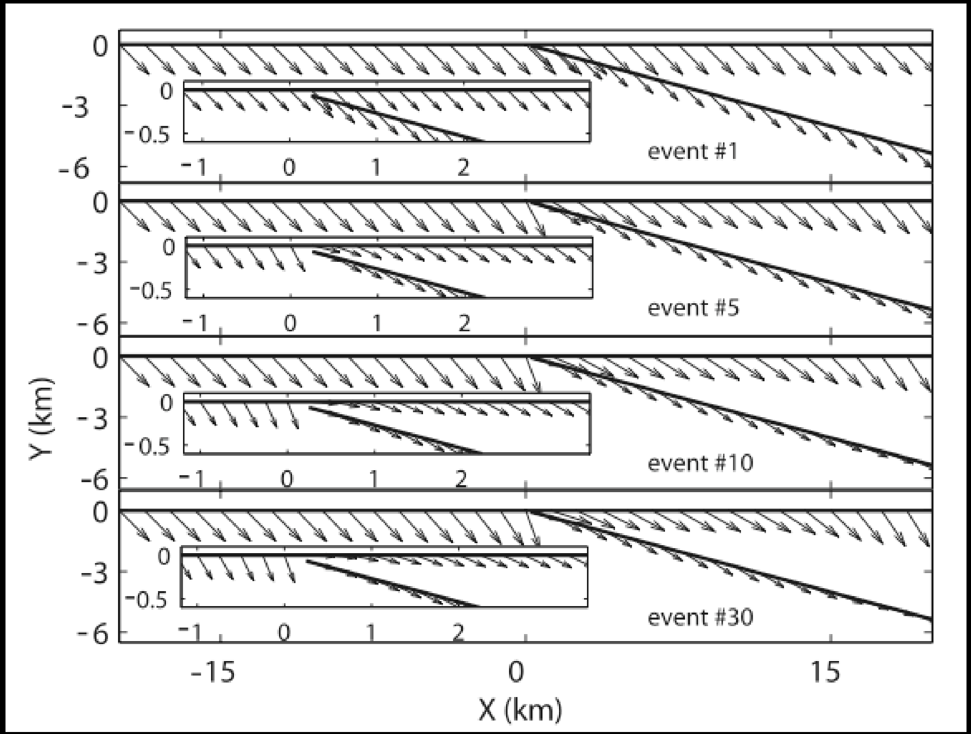
(Kaverina et al., BSSA 2002)

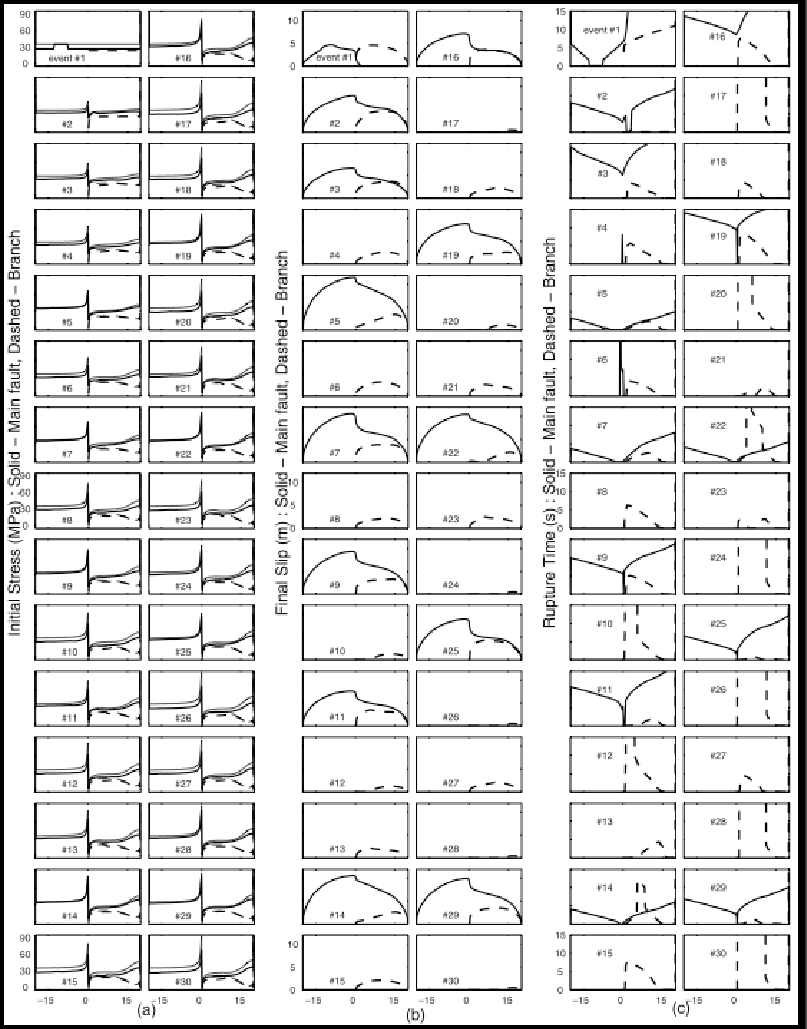
(Oglesby et al., BSSA 2003)



Multiple Earthquake Cycles

- Interseismic viscoelastic model coupled with a coseismic elastodynamic finite element model.
- Backwards branching is observed
- How does the principal stress orientation evolve over multiple earthquake cycles?





(Duan & Oglesby, JGR 2007)

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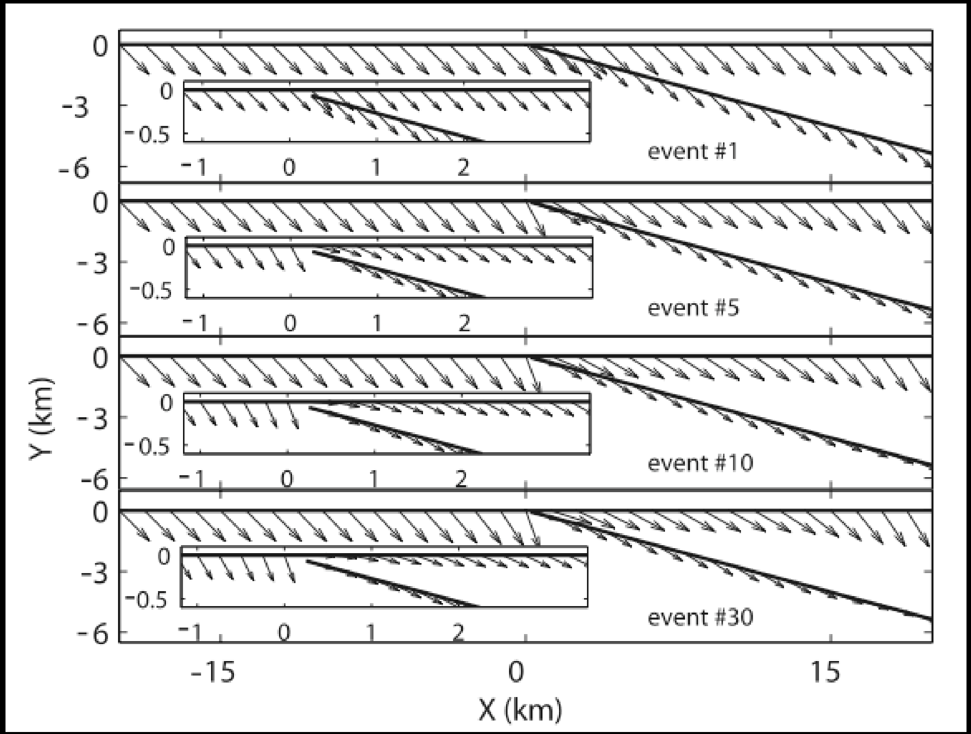

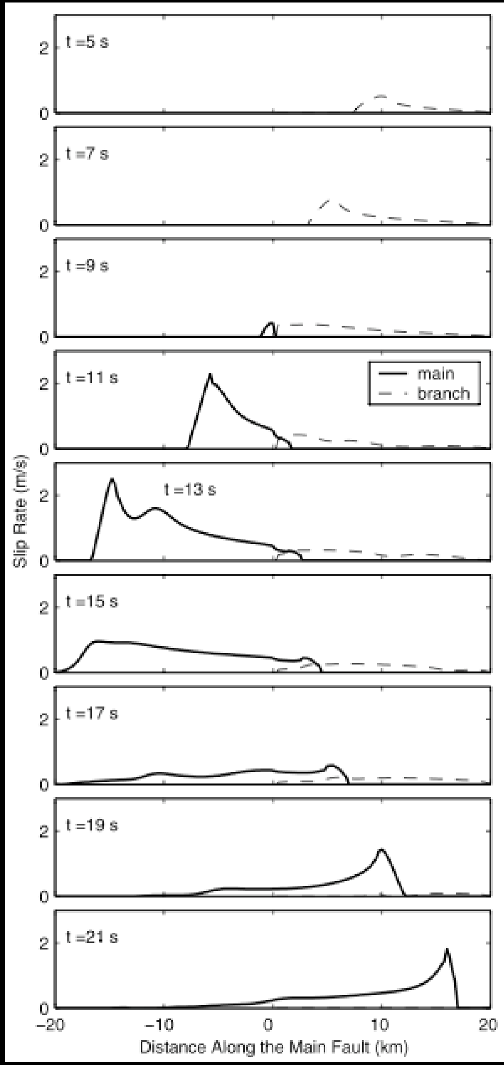

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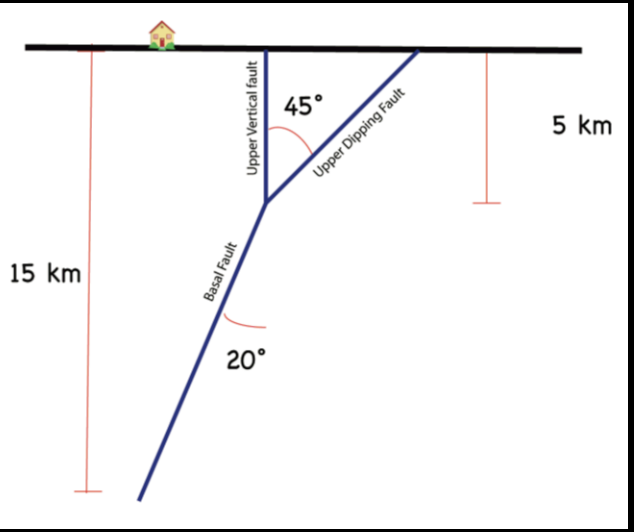
Oblique Slip Partitioning

- Without a barrier to rupture, oblique slip accumulates on the vertical fault.
- With the introduction of a barrier, slip naturally partitions into strike slip and dip slip motions on the vertical and dipping faults respectively



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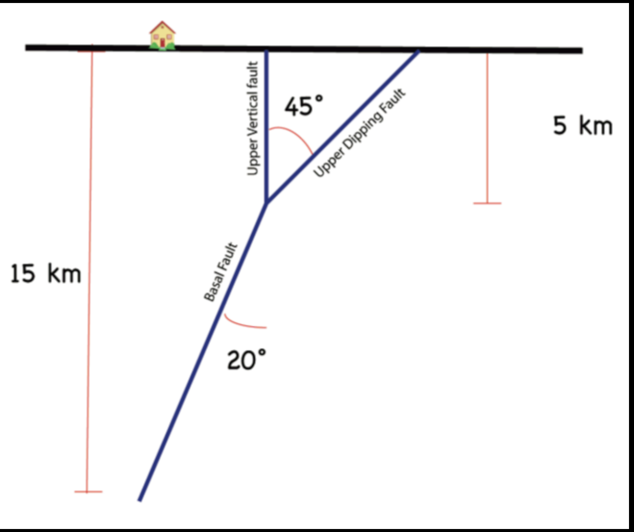

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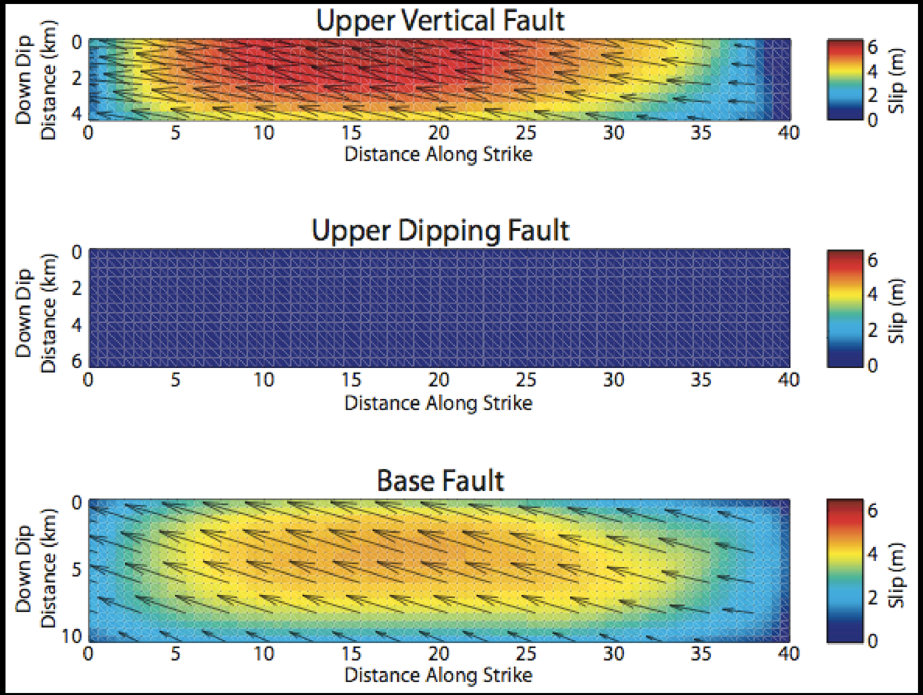

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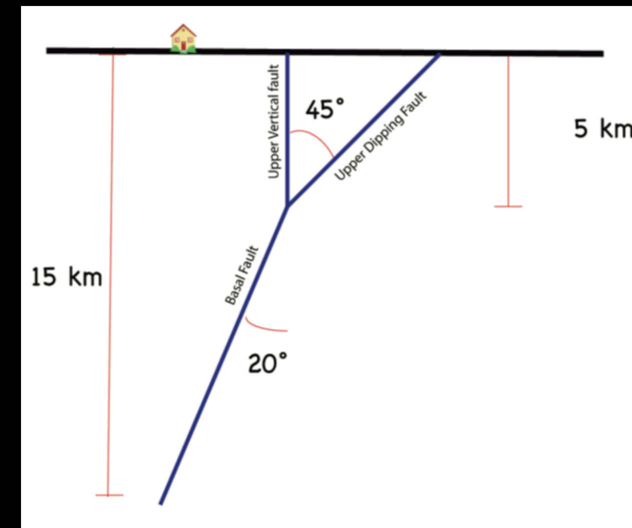

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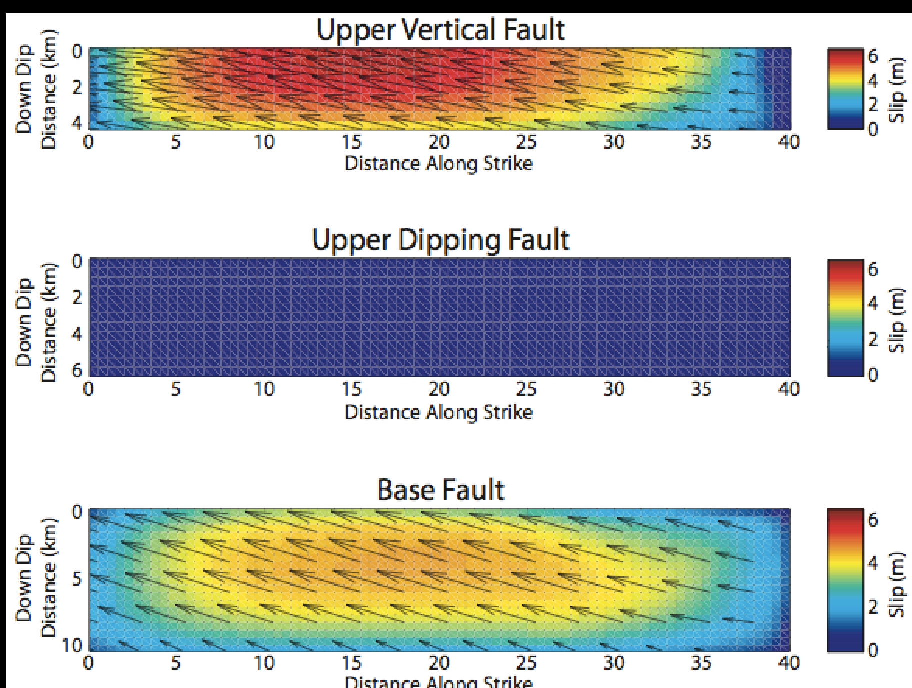

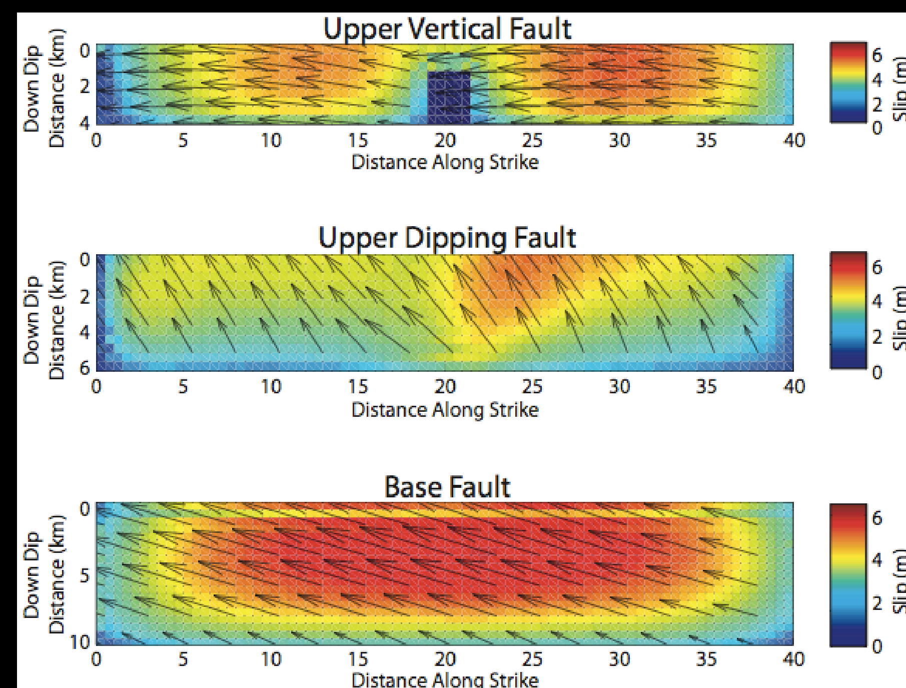

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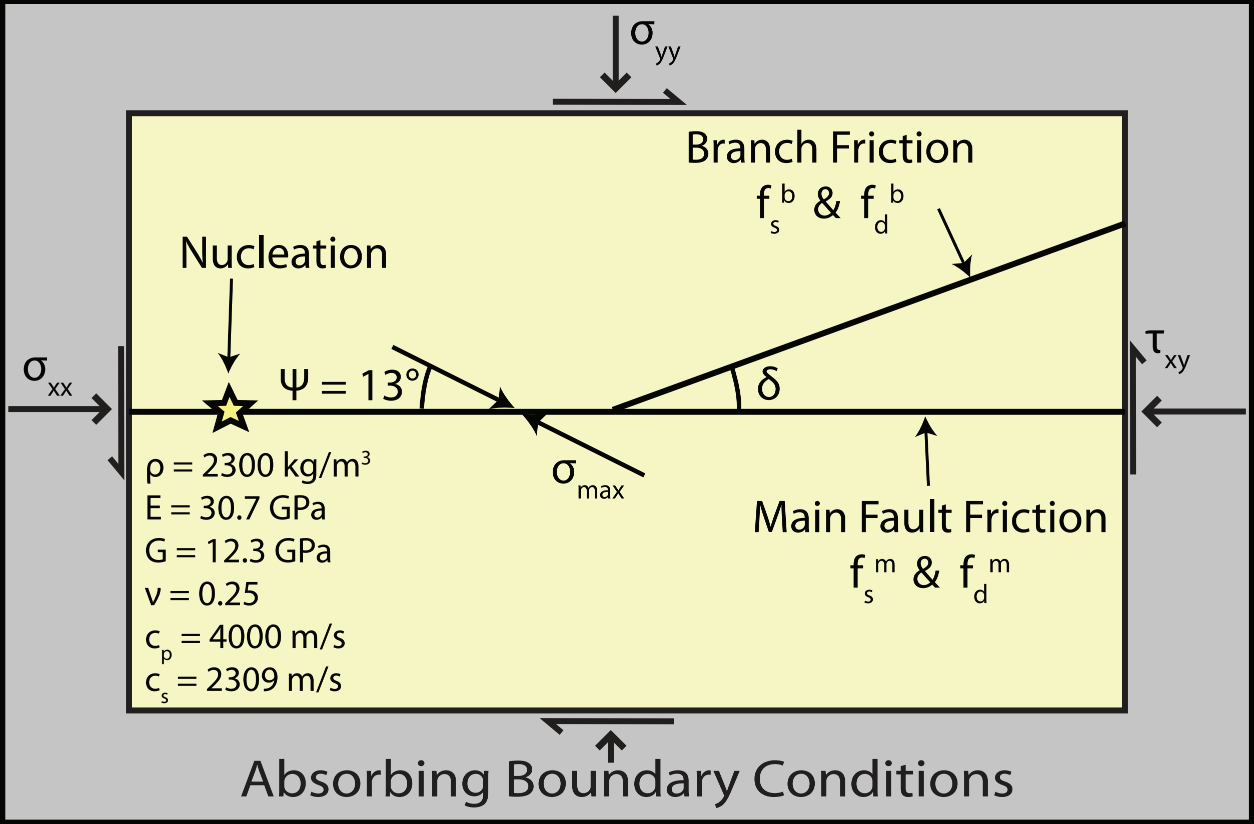
Model Setup



We use 2D plane strain Finite Elements to model the dynamic rupture path selection of an earthquake

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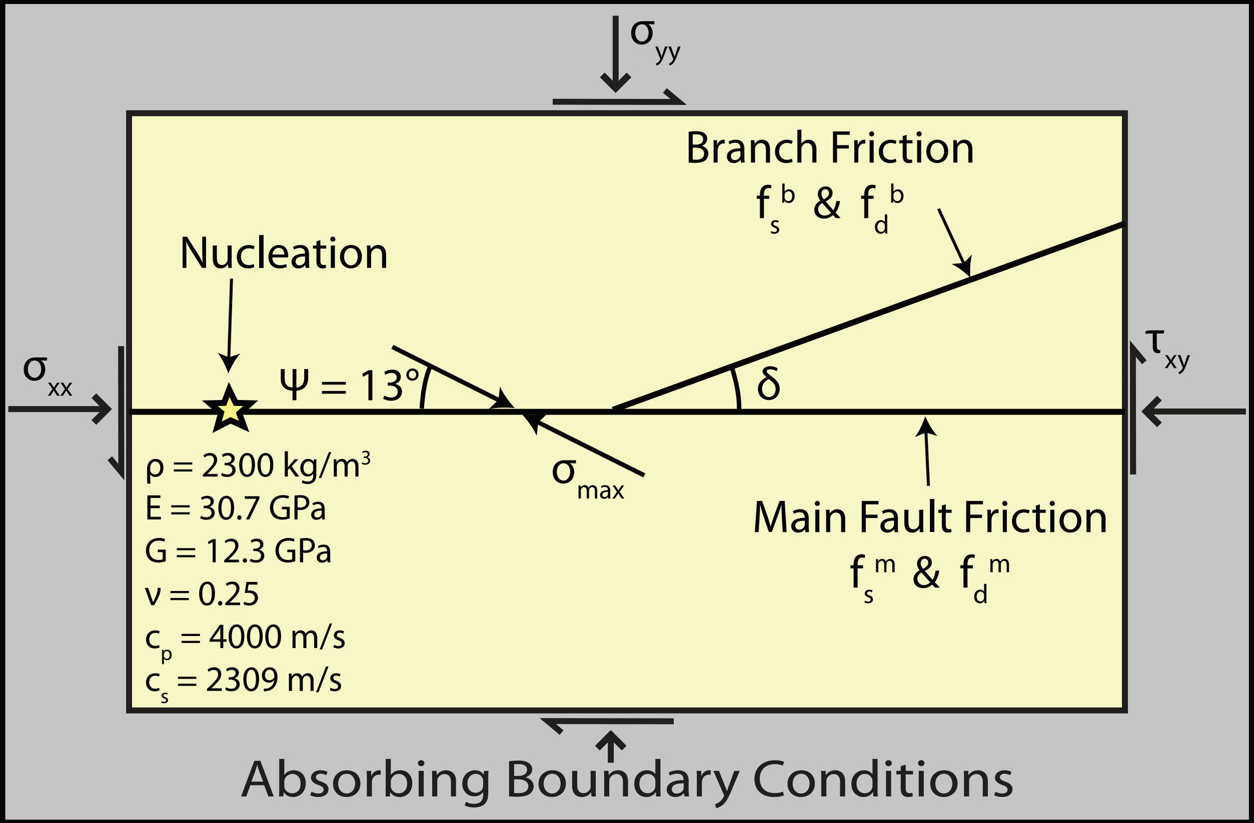

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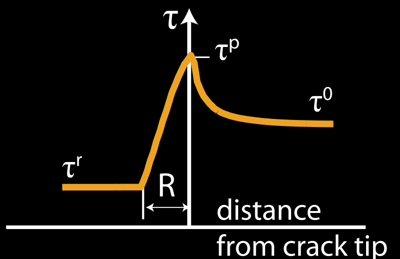
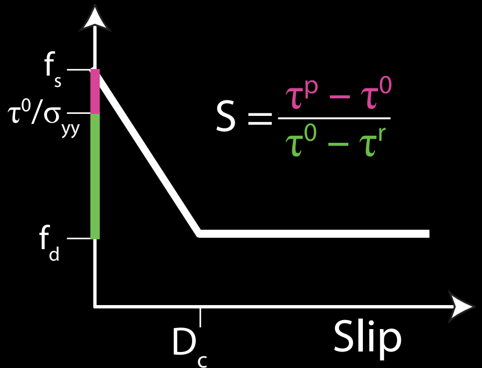
Slip Weakening Zone Size



$R = R_0$ at low speed and high S

$$R_0 = \frac{3\pi}{8}\frac{\mu}{\tau^p - \tau^r}D_c$$

Linear Slip Weakening of Friction Coefficient



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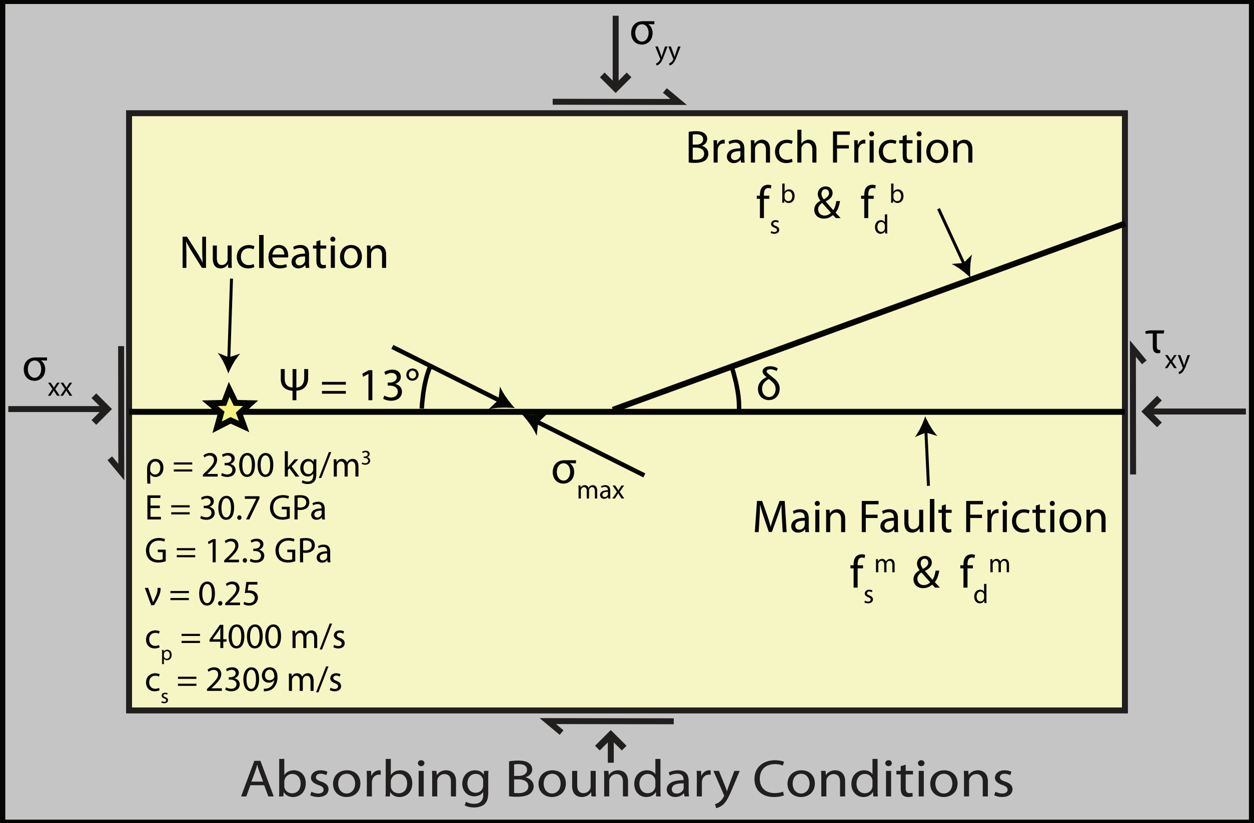

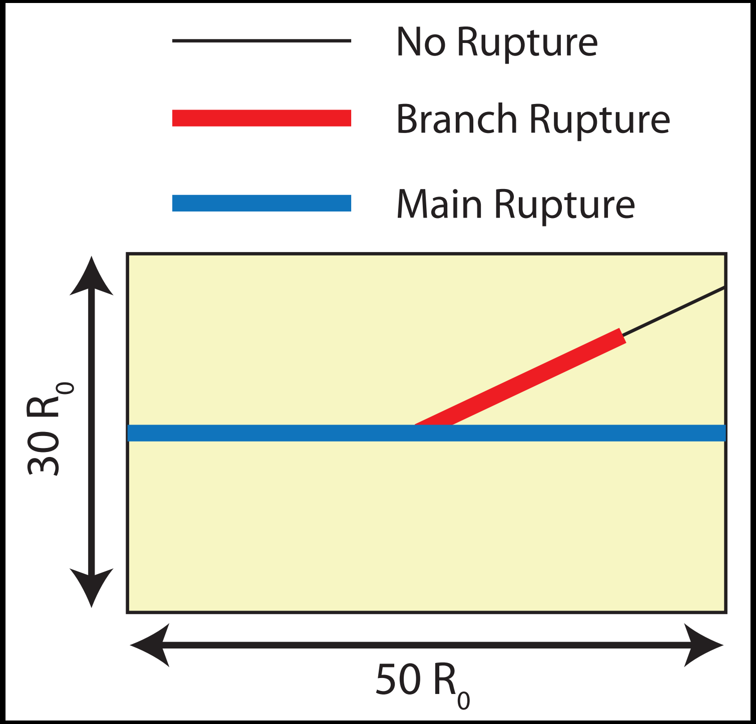

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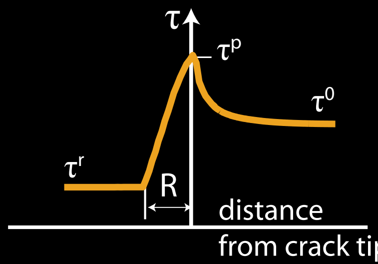

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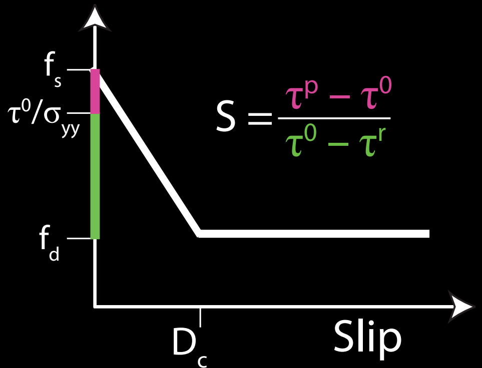
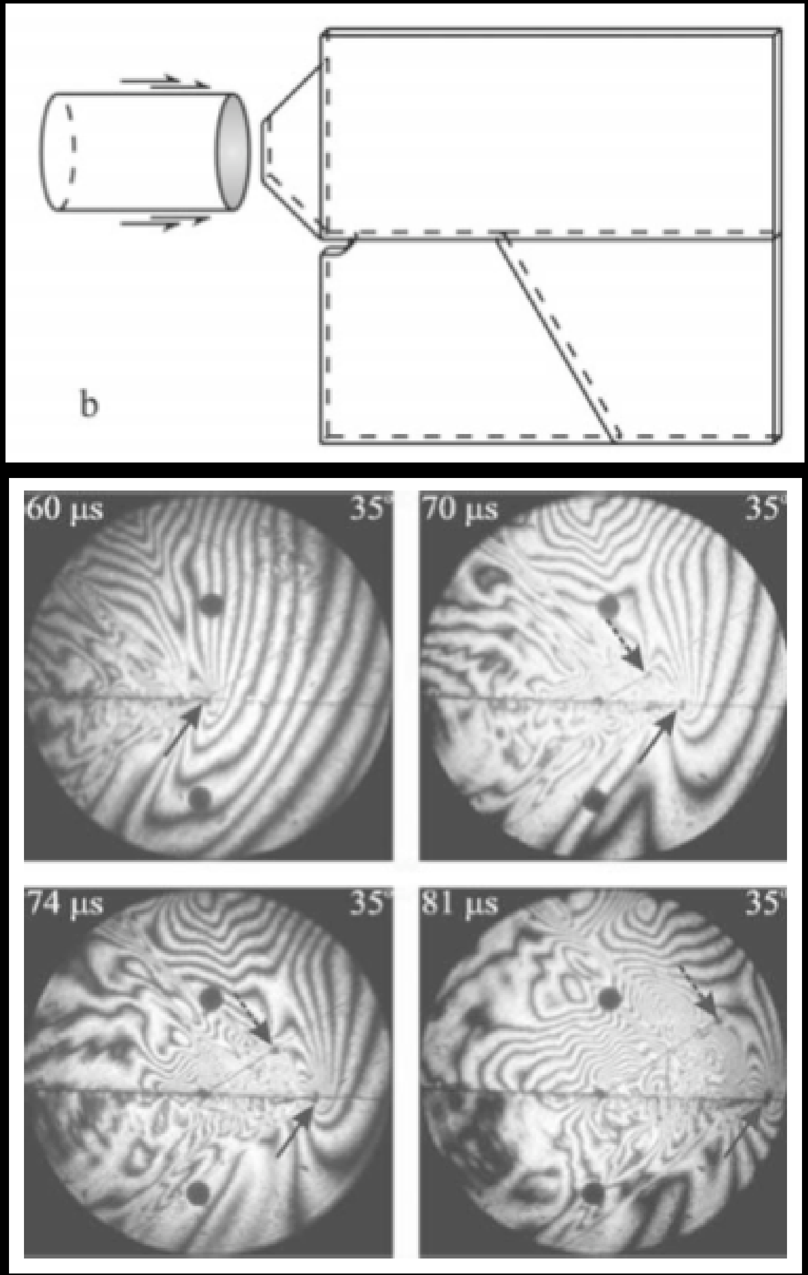


$$S = \frac{\tau^p - \tau^0}{\tau^0 - \tau^r}$$

Laboratory Experiments



- Mode II ruptures are simulated in the laboratory using a projectile and Homalite plates with predefined failure planes.
- This setup differs from that of natural faults in that there is no confining stress.
- For supershear ruptures, the mach cone from the main fault rupture can sustain rupture on the branching fault.

(Rousseau & Rosakis, JGR 2009)

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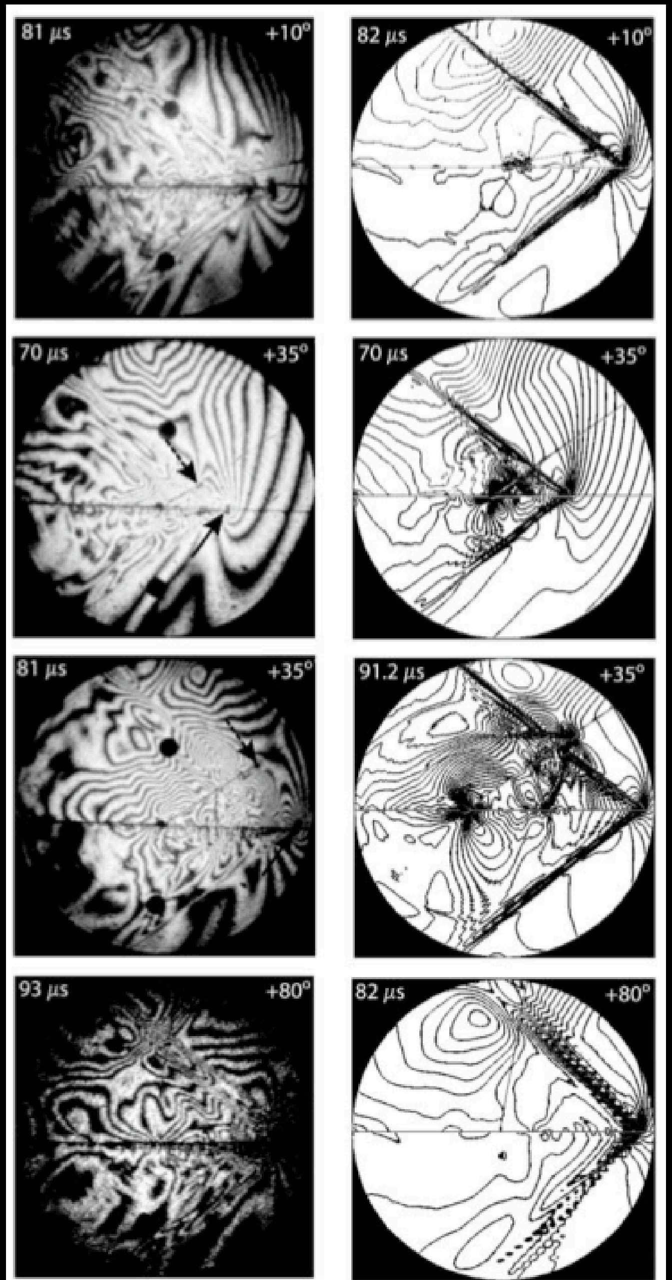

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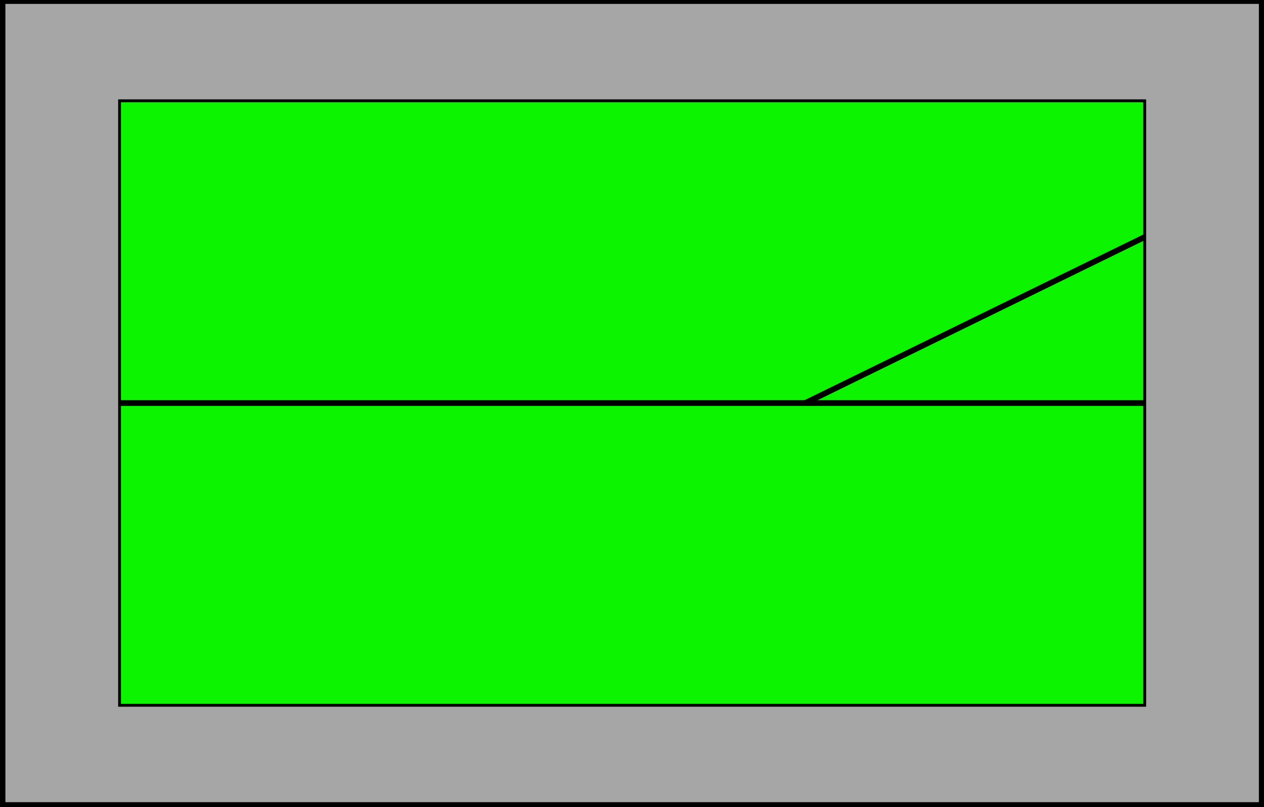
(Templeton et al., JGR 2009)

Gradient FE Mesh



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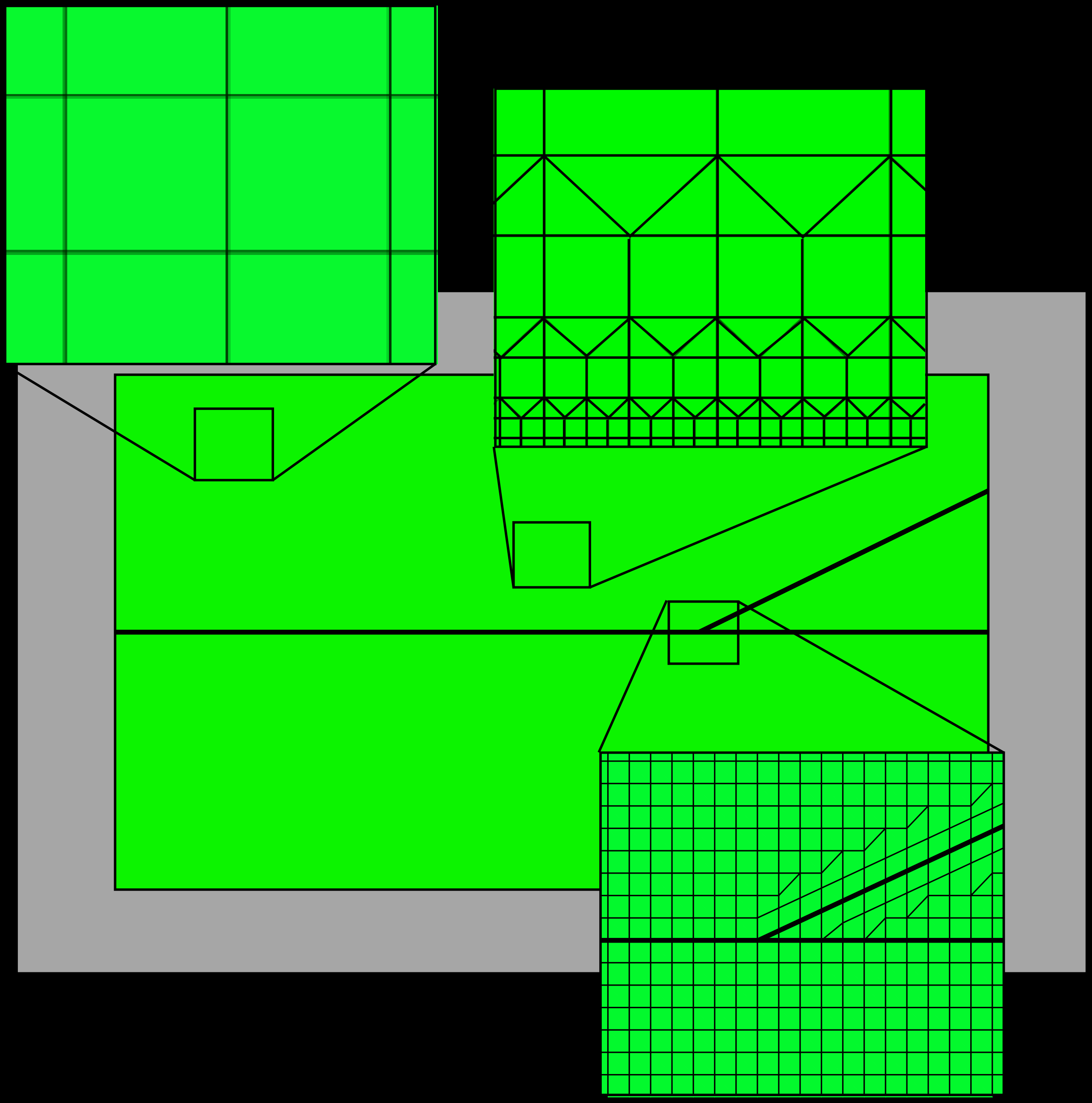
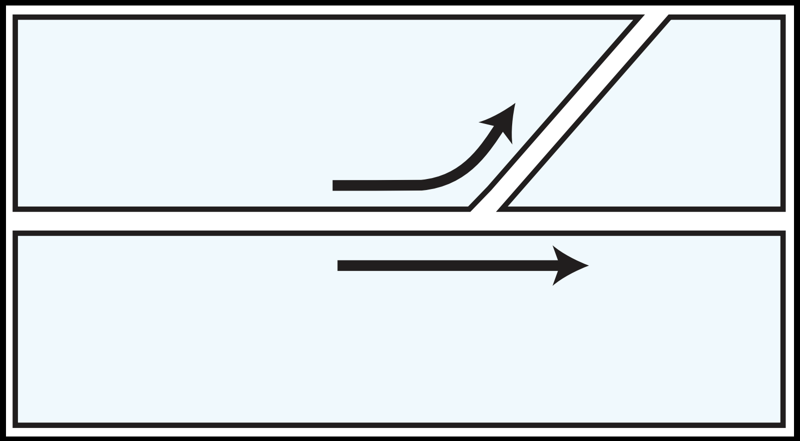


Branch Junction Definition



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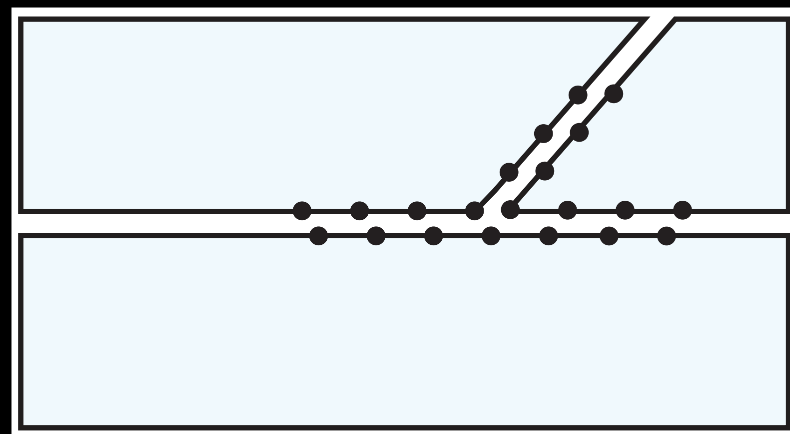

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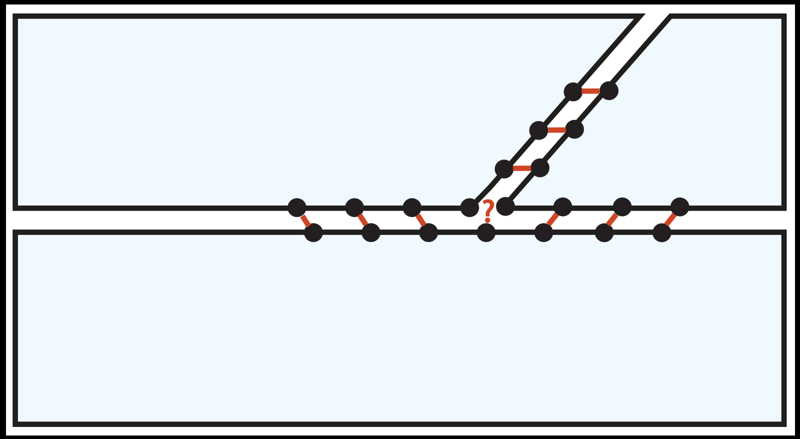

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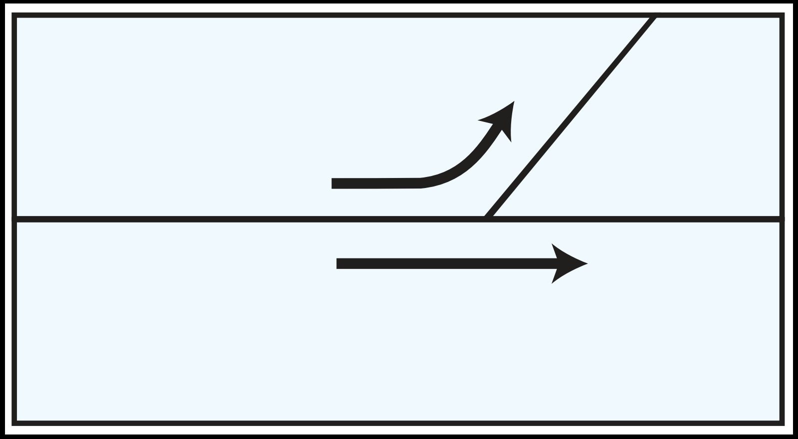

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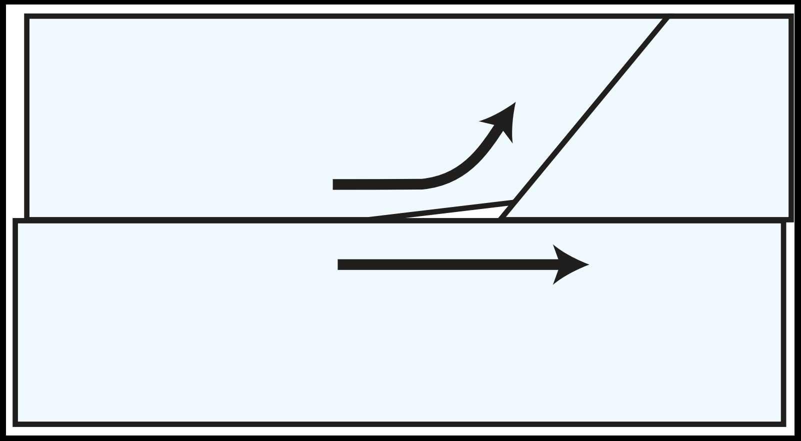

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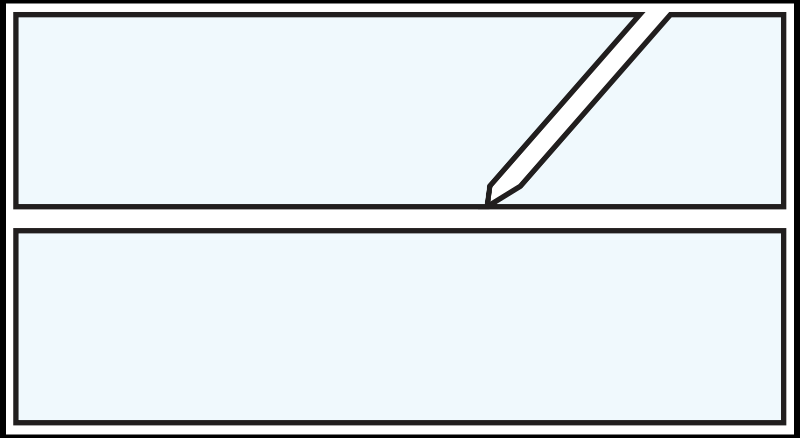

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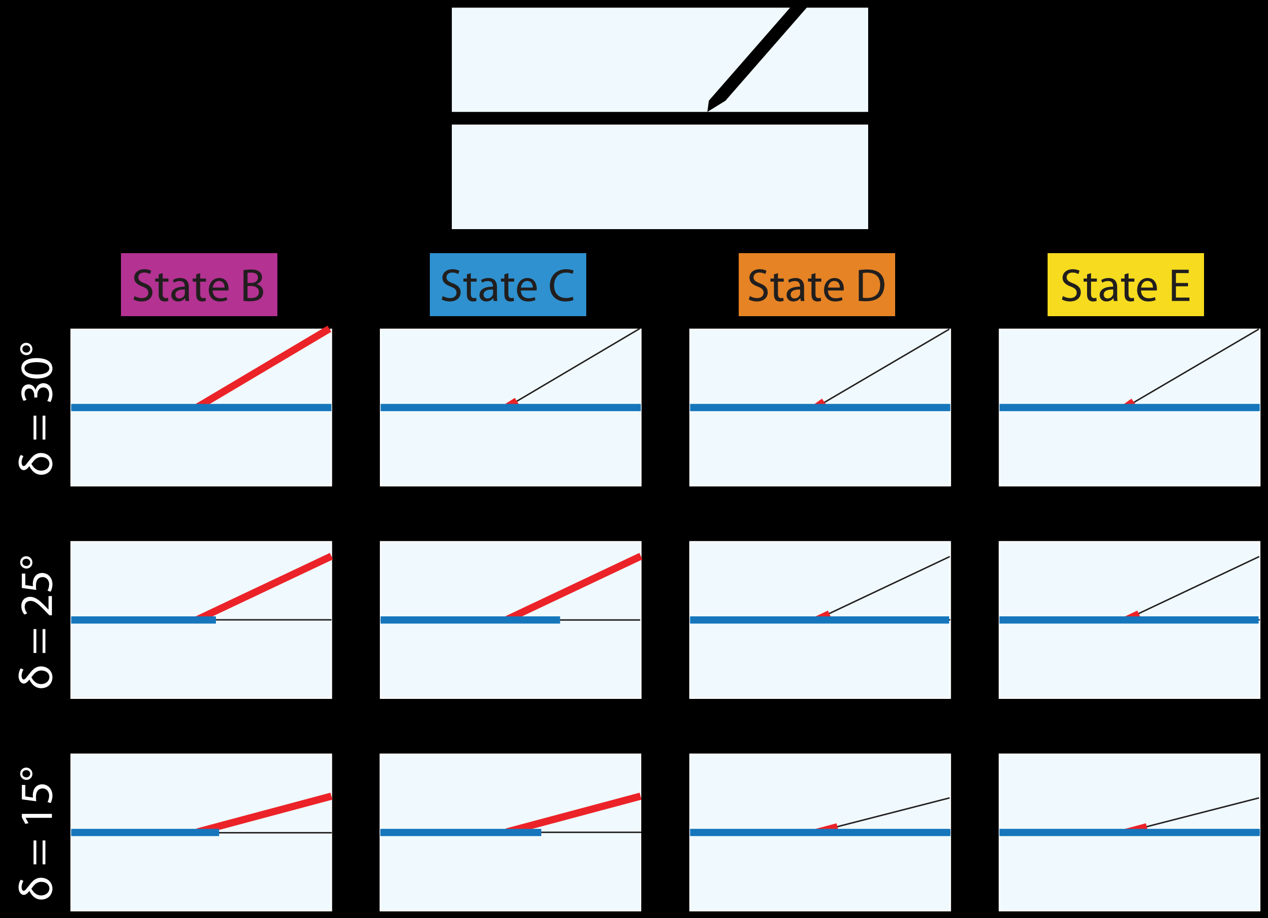

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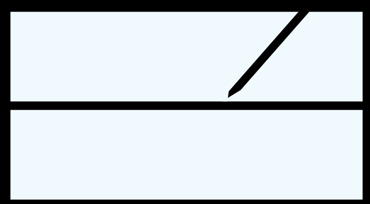

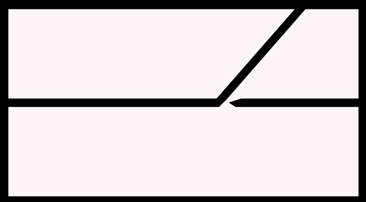

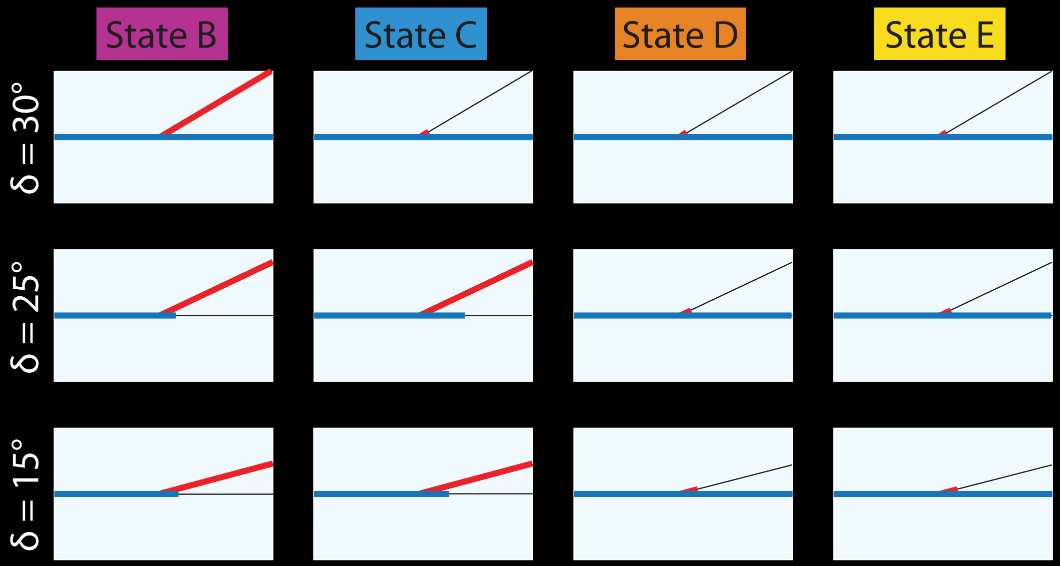

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- Our model does not inhibit opening, which often occurs for the low prestress angles we use, so we investigate the role of our modeling choice.

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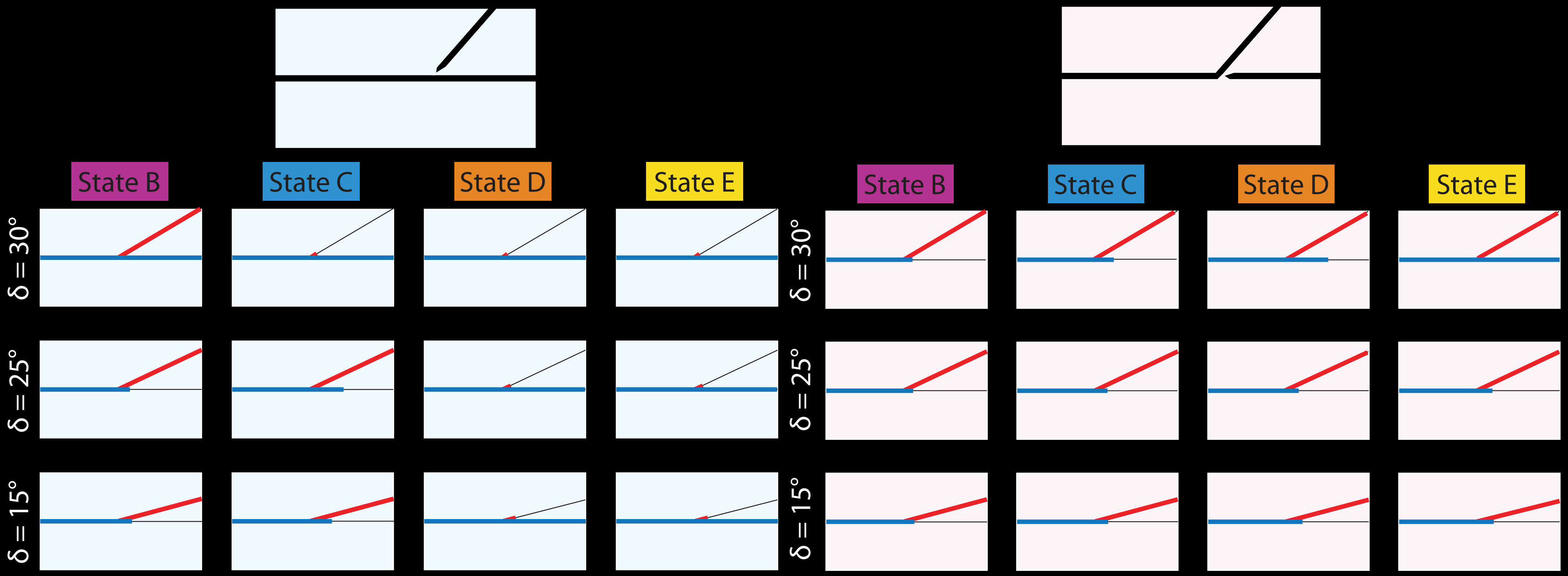

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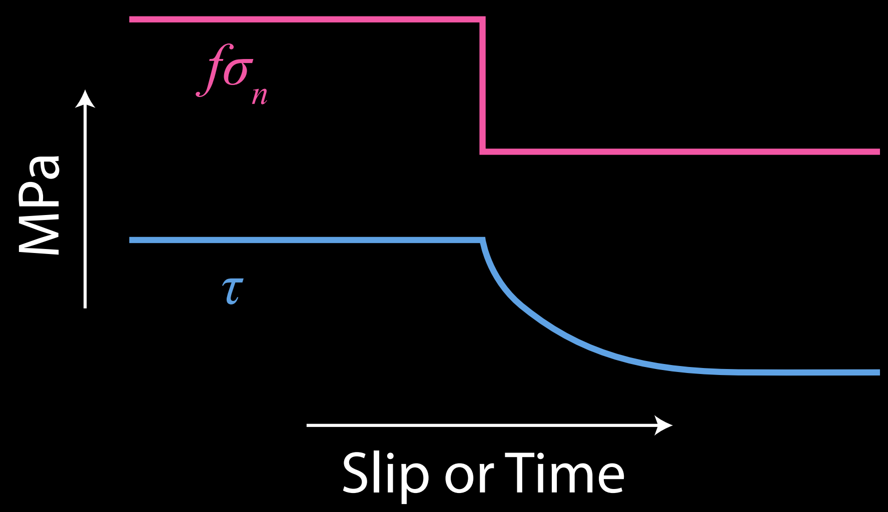
Regularized Friction

Simplified Prakash-Clifton Law



Shear stress evolves over some time scale t*

$$\frac{d\tau}{dt} = -\frac{1}{t^*}\left[\tau - f(\sigma - p)\right]$$

Regularized Friction

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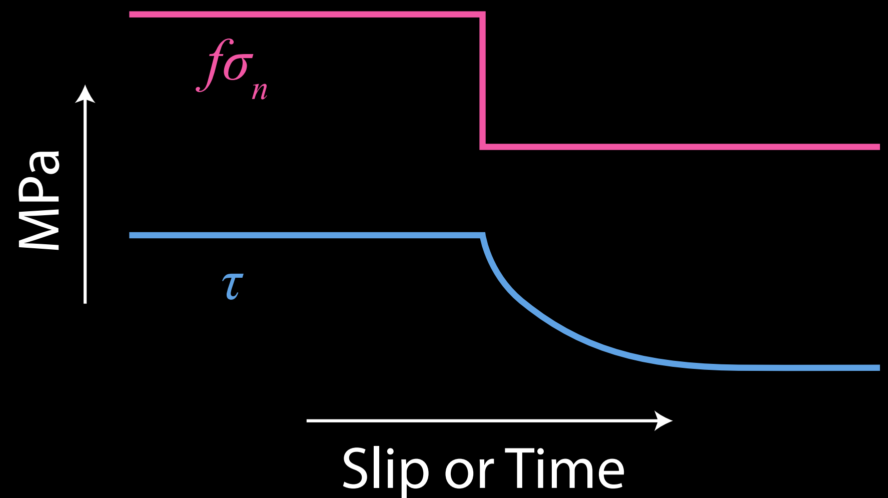

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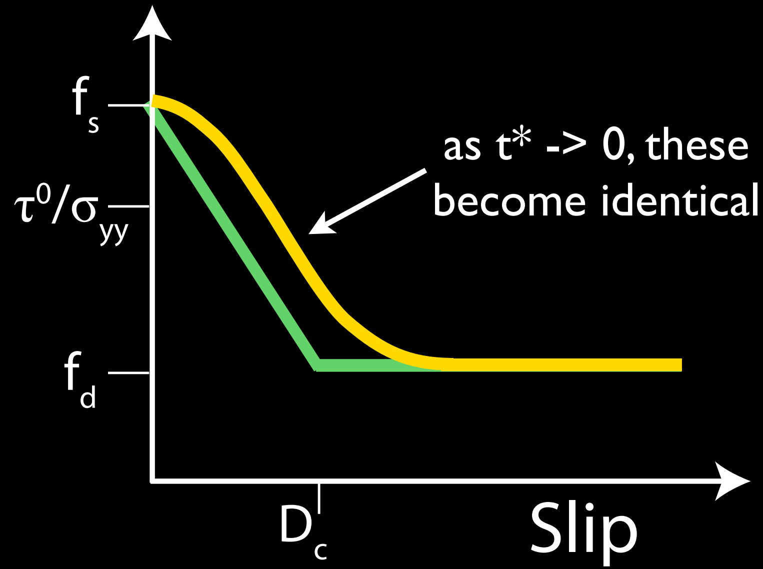
Regularized Slip Weakening



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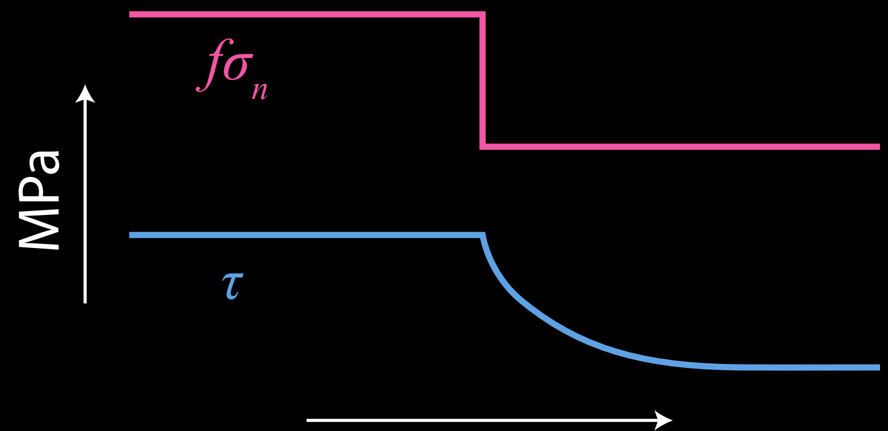


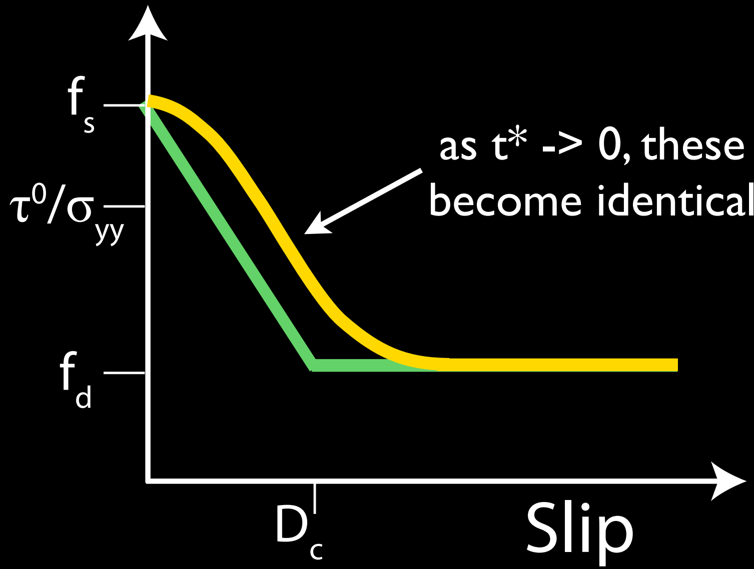
Shear stress evolves over some time scale t*

$$\frac{d\tau}{dt} = -\frac{1}{t^*}\left[\tau - f(\sigma - p)\right]$$

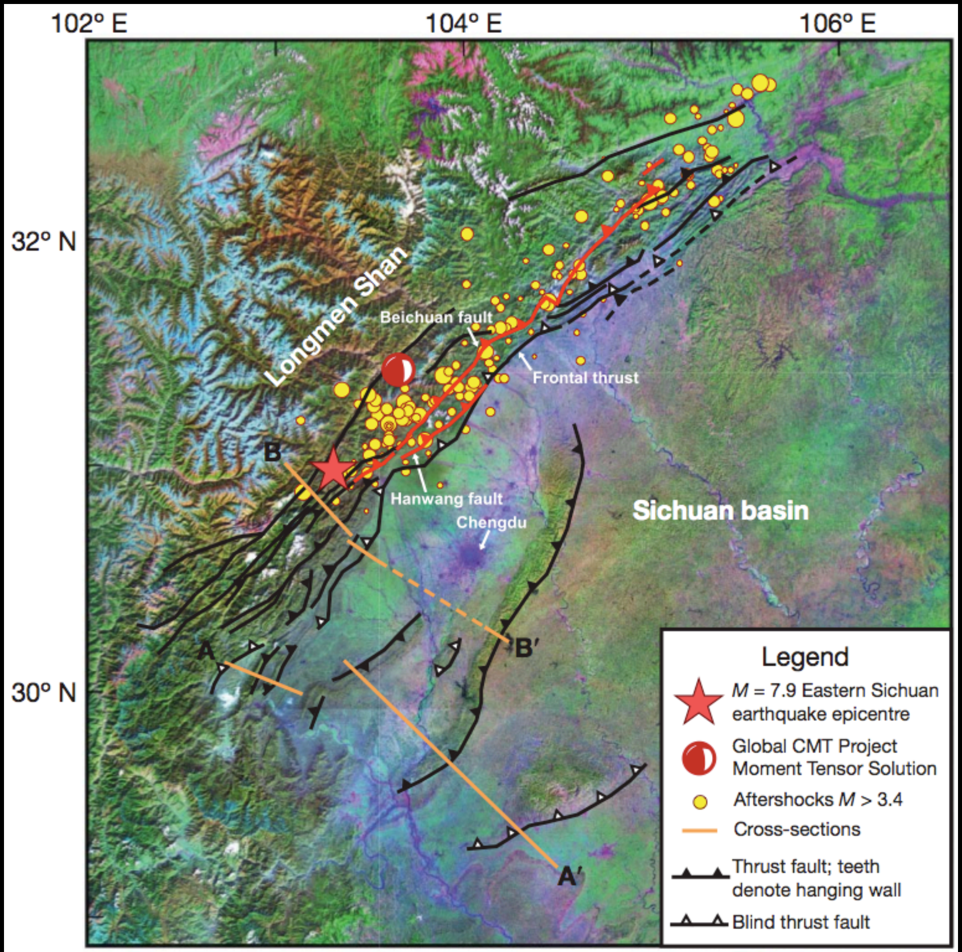
We choose t* such that:

- t* > timestep
- t* << duration of slip weakening
- t* = 2 Δx / Cs

Regularized Slip Weakening



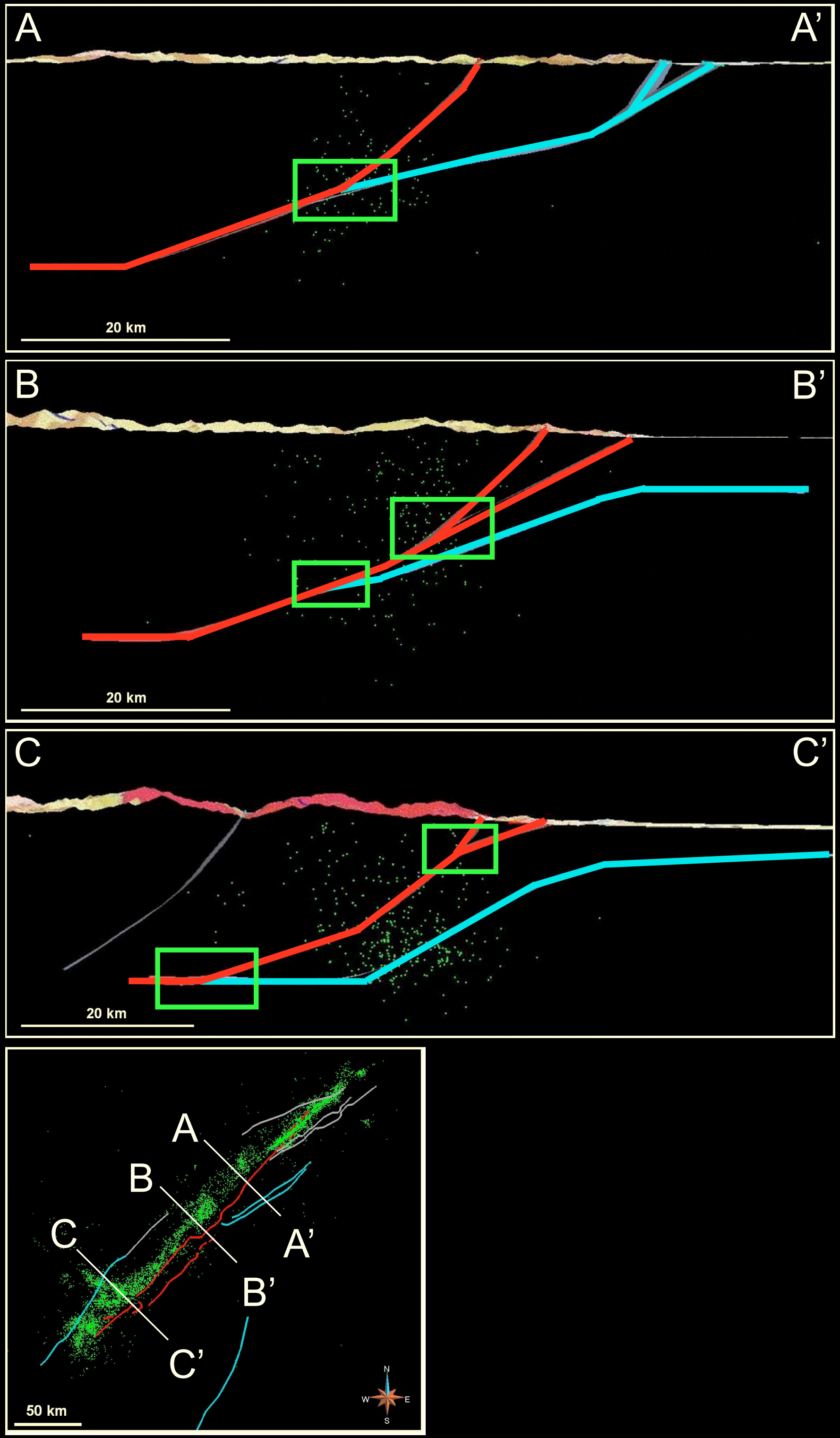
Wenchuan



(Hubbard et al., Nature 2009)

- Seismic reflection data is used to constrain the existing fault geometry and the surface rupture indicates that a variety of branching geometries were encountered during the Wenchuan earthquake.
- We assume a rupture velocity and a horizontal maximum prestress orientation.

Wenchuan



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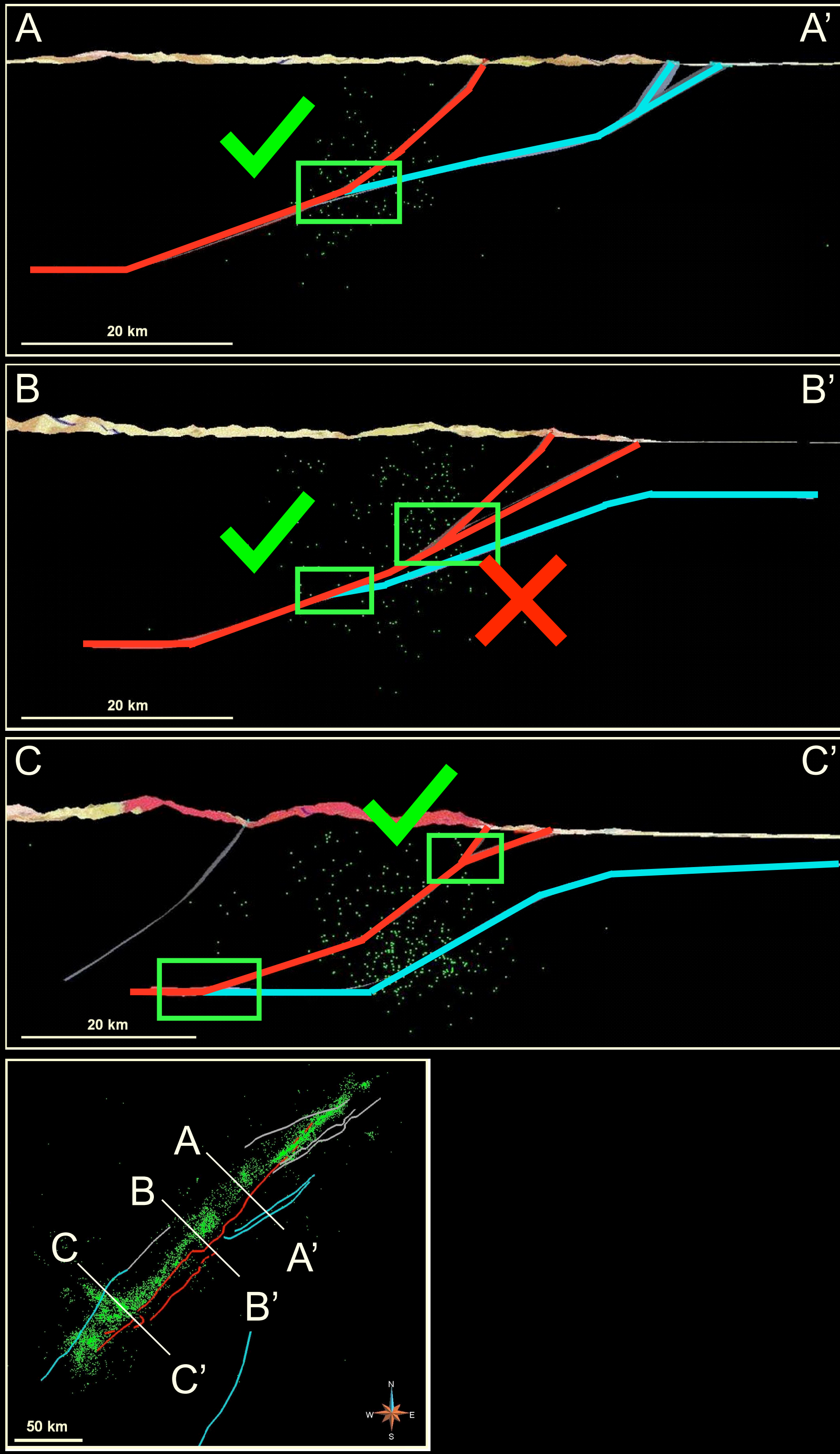

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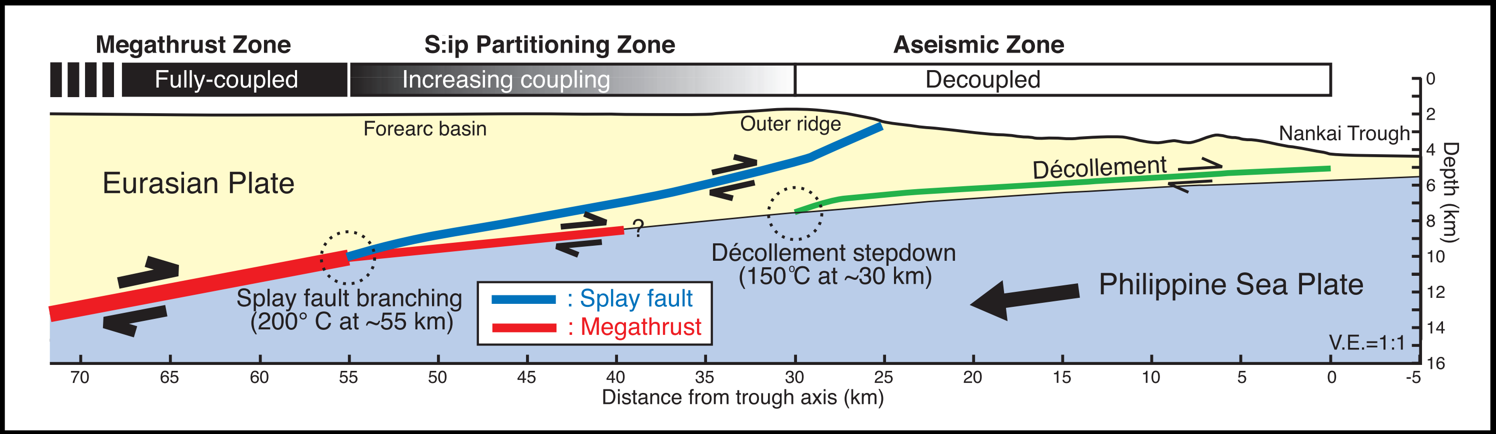
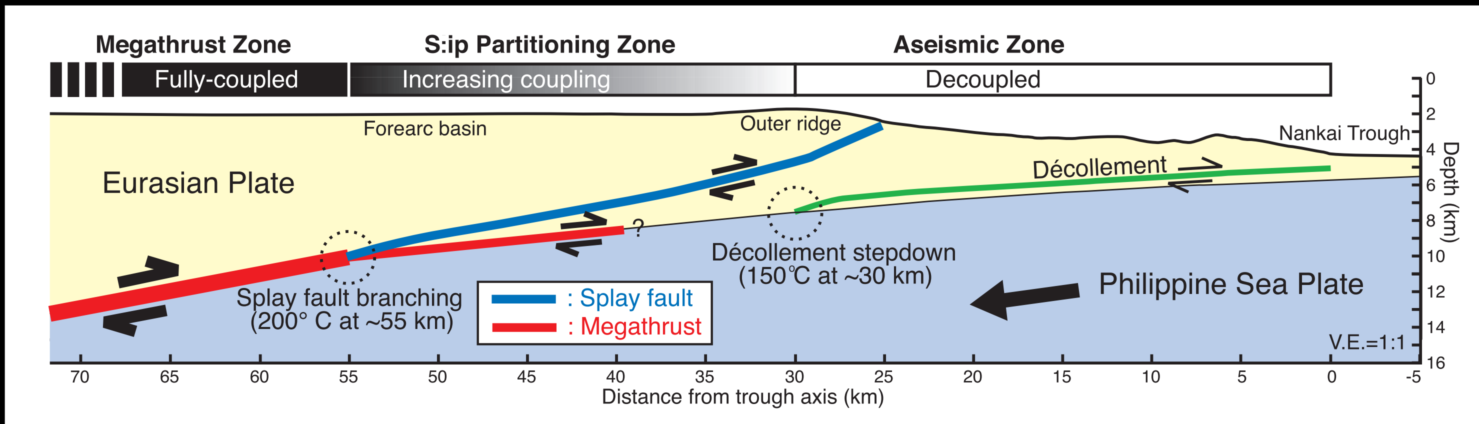
Subduction Zones



(Park et. al, Science 2002)

Are splay faults activated coseismically?

Subduction Zones



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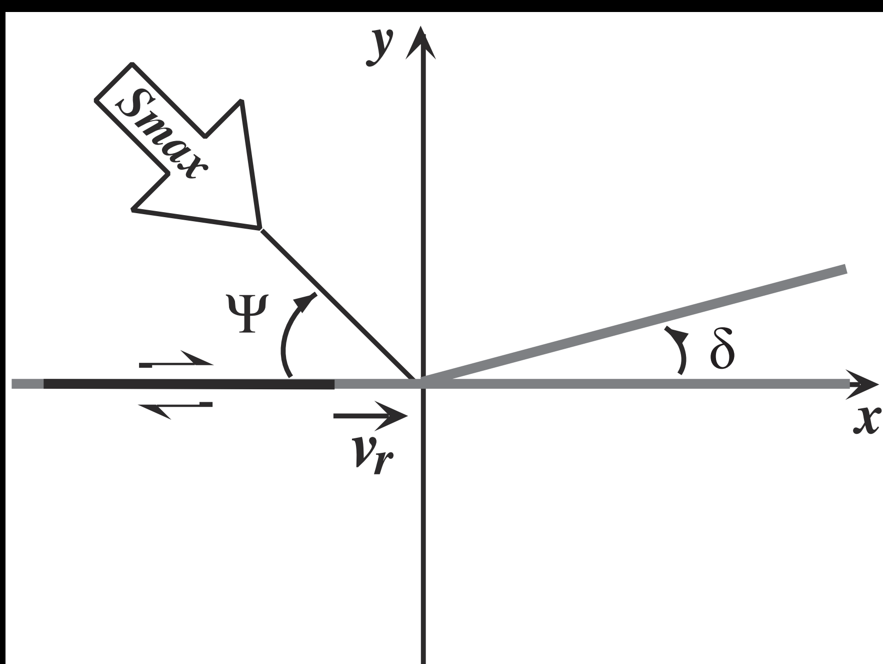


(Kame et al., JGR 2003)

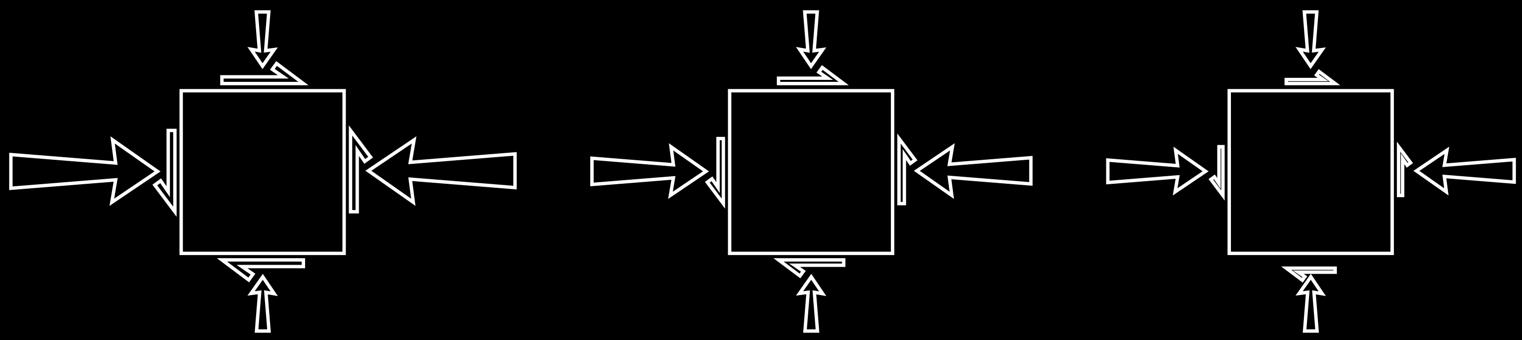
We know some important parameters:

- Step-up angle
- Rupture Velocity
- Principal Stress Orientation

But what about:

- Friction Values?
- Material Properties?
- Plastic Deformation?

Stress States and Friction Values



	A	B	C	D	E	F
σ_{xx}/σ_{yy}	2.48	2.31	2.20	2.11	2.04	1.98
$-\tau_{xy}/\sigma_{yy}$	0.36	0.32	0.29	0.27	0.25	0.24

Low S Ratio → High S Ratio

Constant Stress Orientation: $\Psi = 13°$

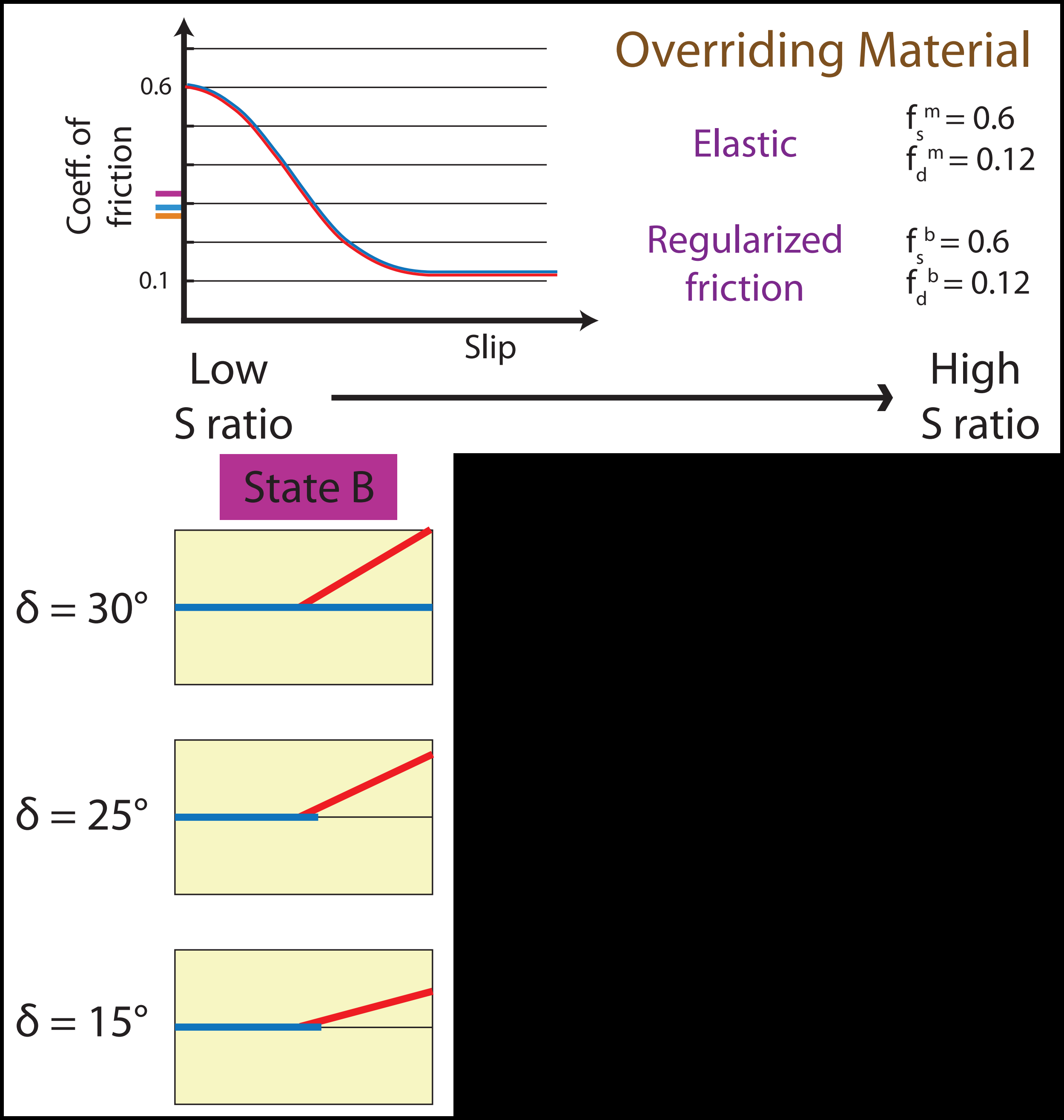
Variable Stress State

Constant Rupture Velocity at Branching Junction: $0.86\ c_s$

Variable Static Friction: 0.6, 0.5, 0.4

Variable Dynamic Friction: 0.02, 0.12, 0.22

Effect of S-ratio



- Identical friction properties on branch and main faults.
- S ratio on the main fault influences rupture path selection.
- Low S ratios promote branch activation.

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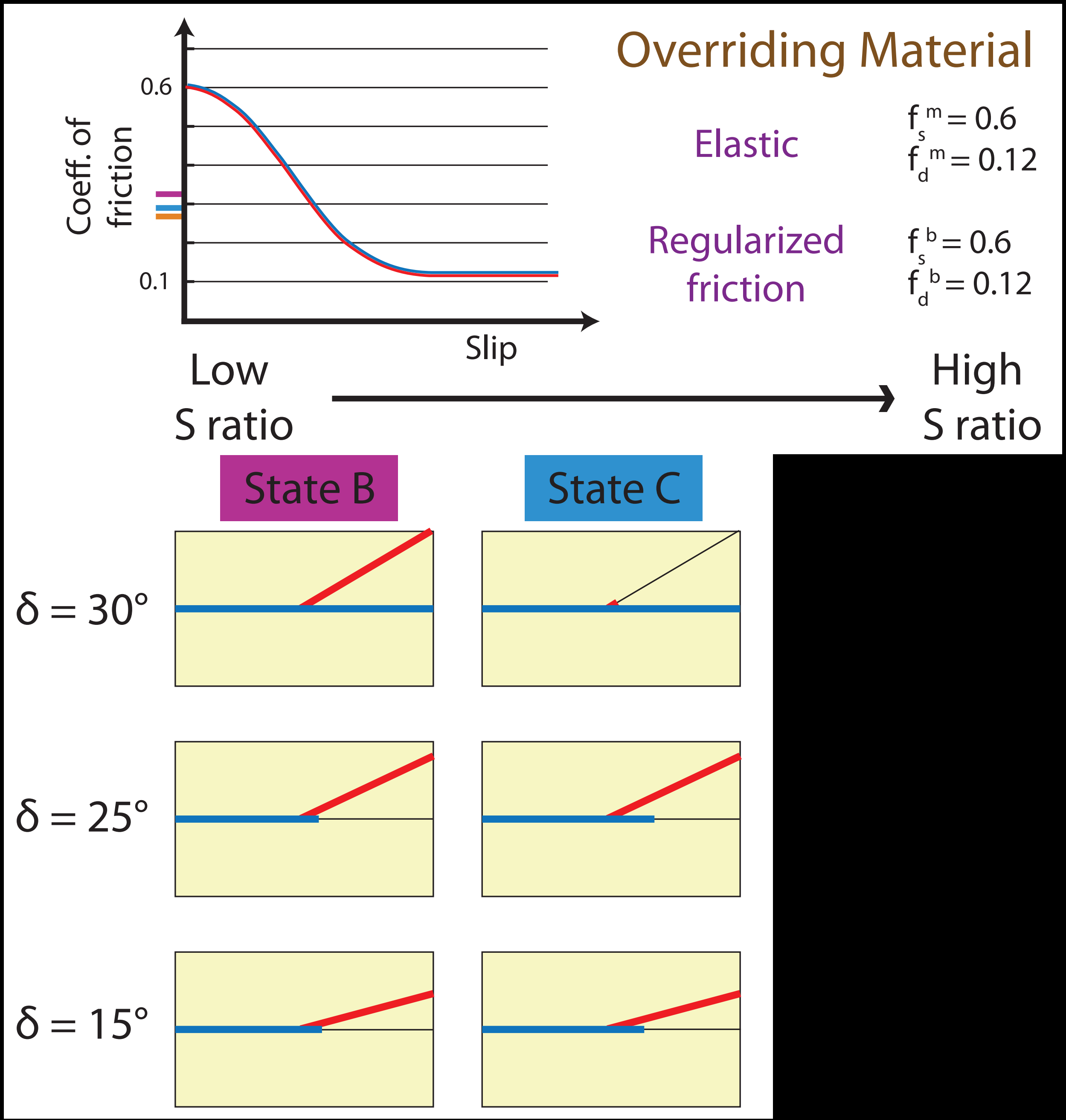

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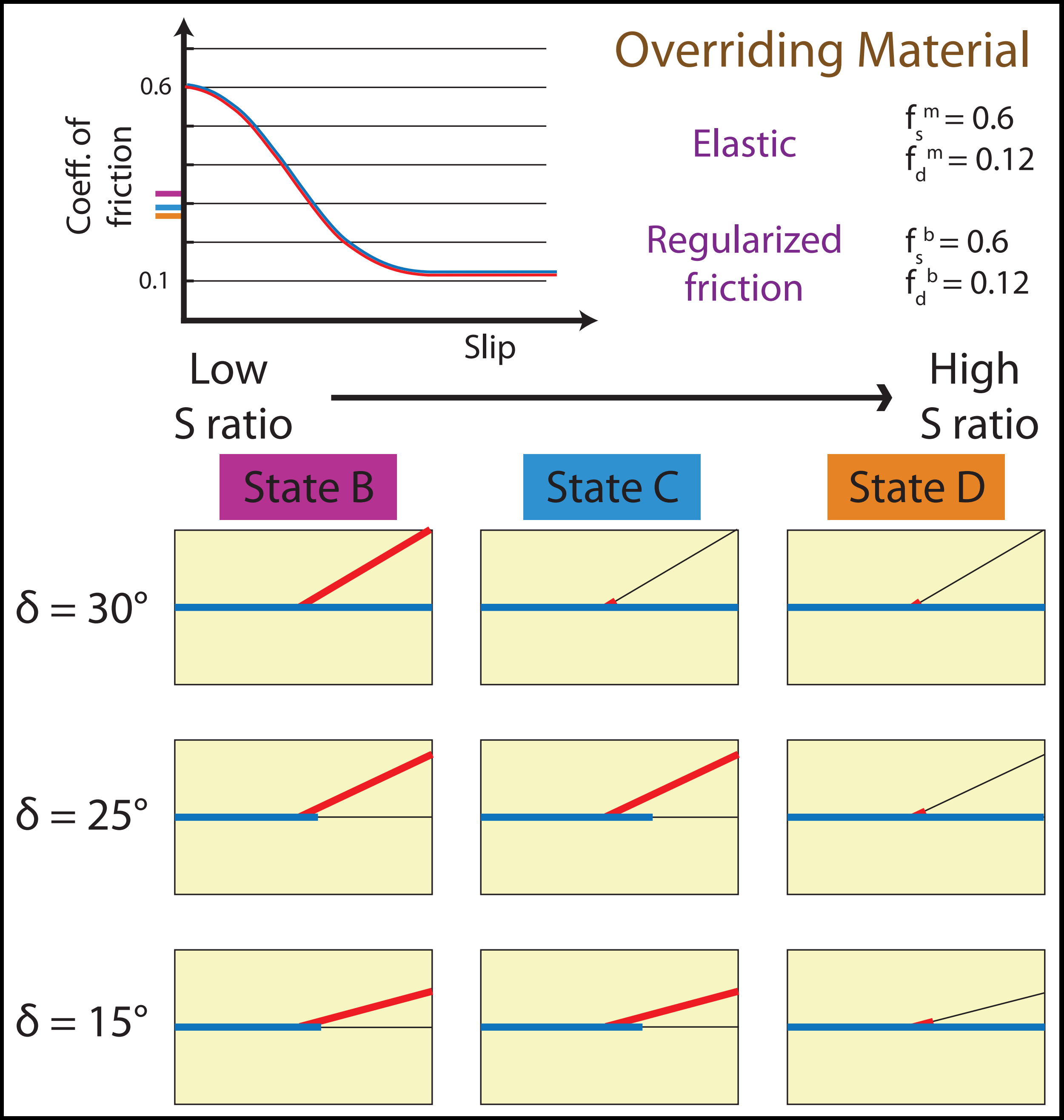

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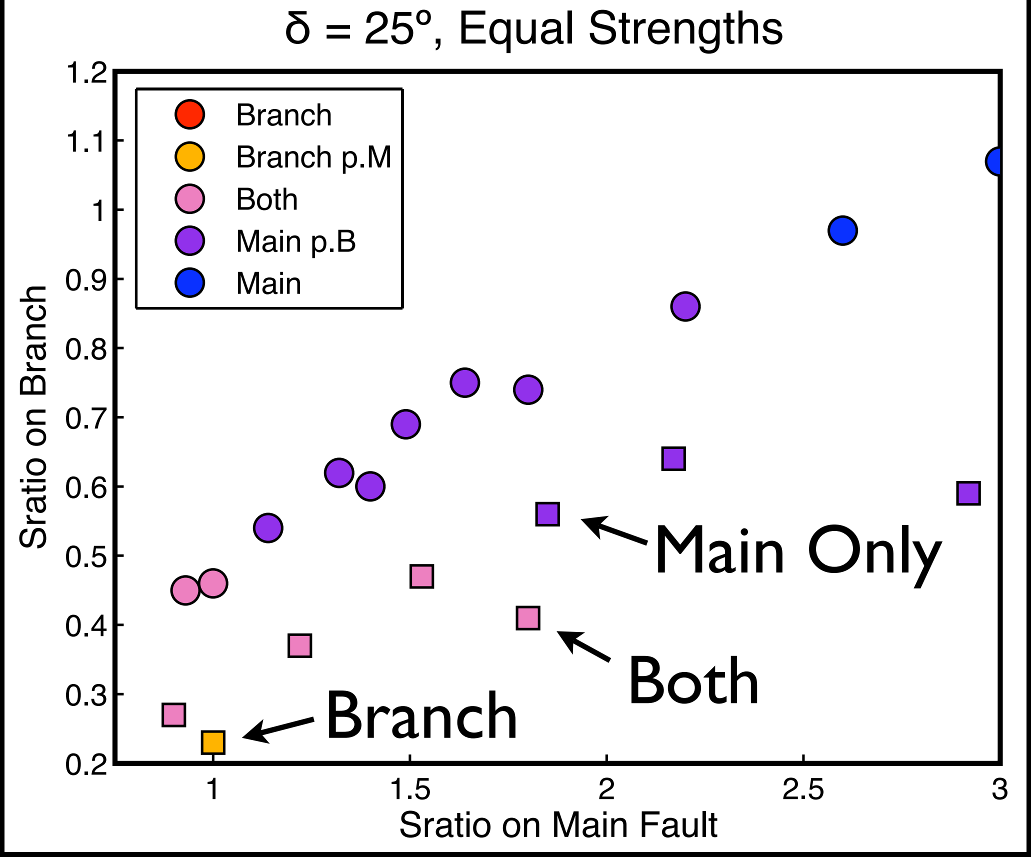
Role of the relative S Ratios?

- Lower S ratios on the main fault and branch promote the continuation of rupture on the branch.
- For equal friction values on the main fault and the branch, an S ratio <~0.54 will result in branch activation.



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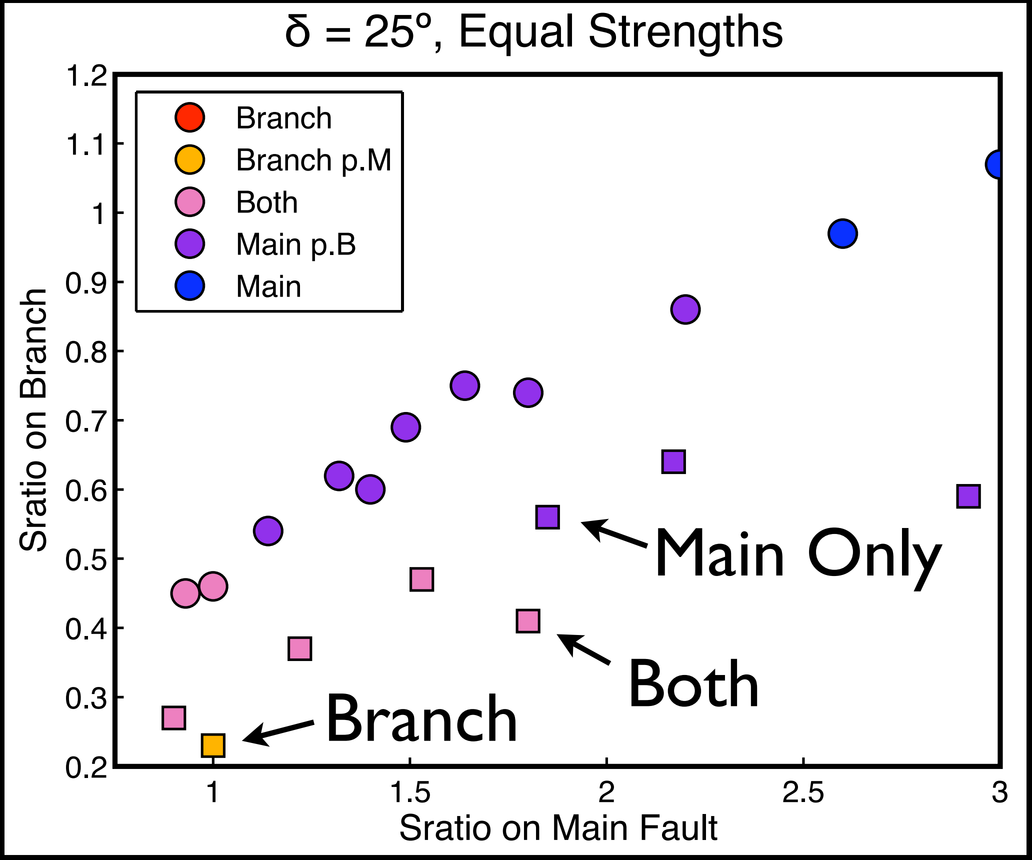

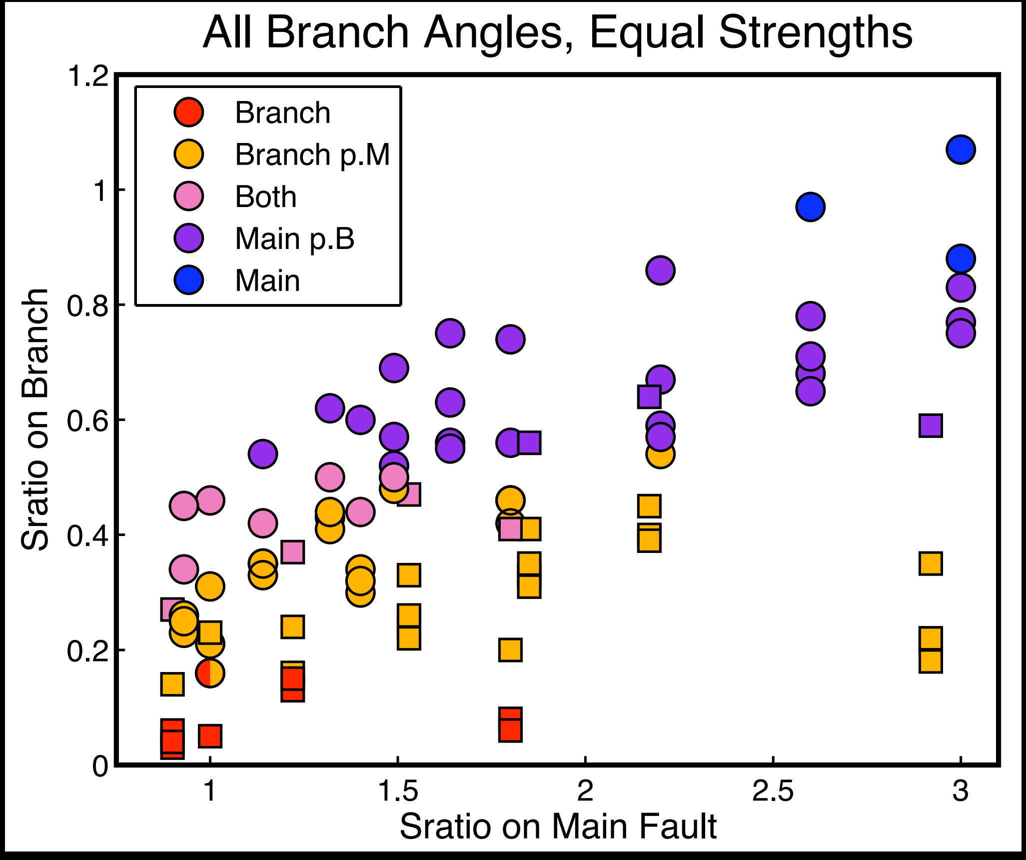

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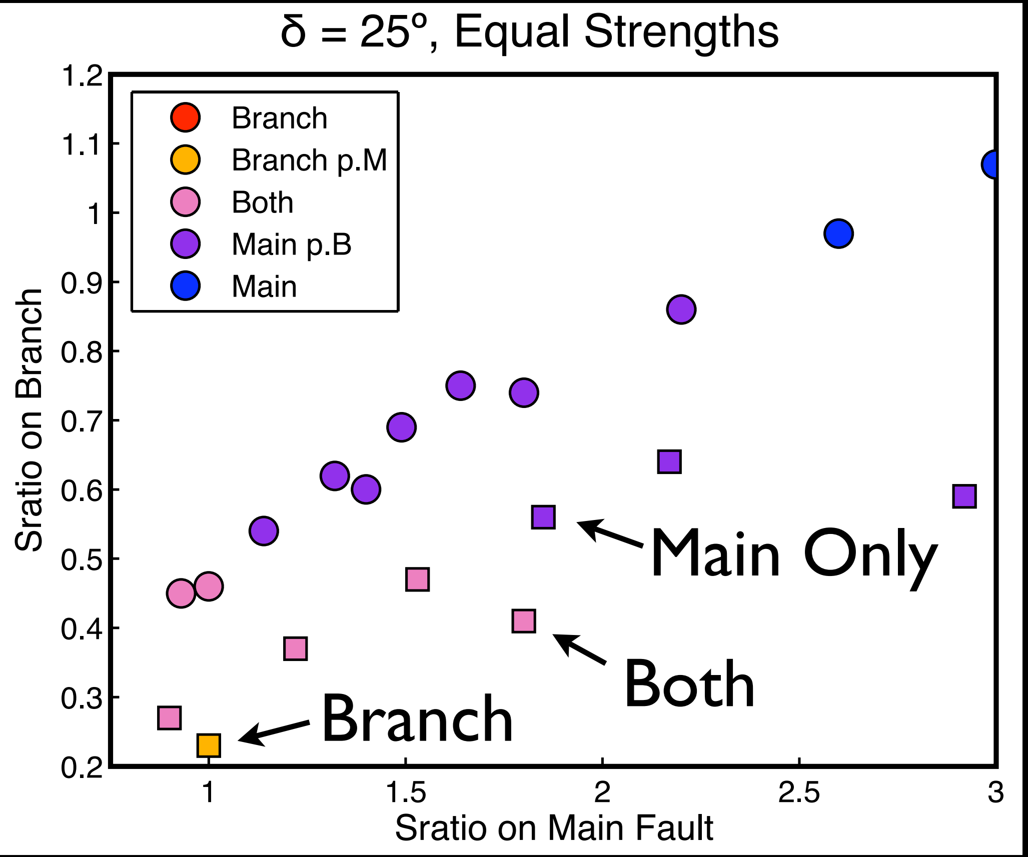
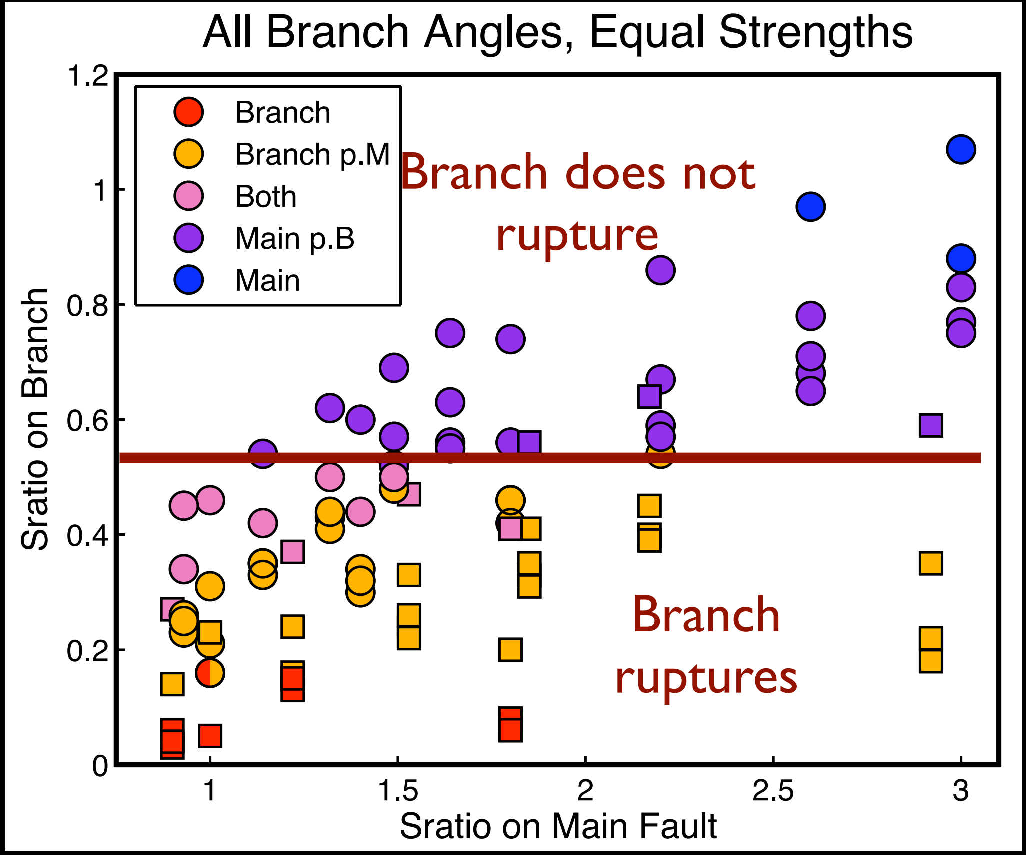
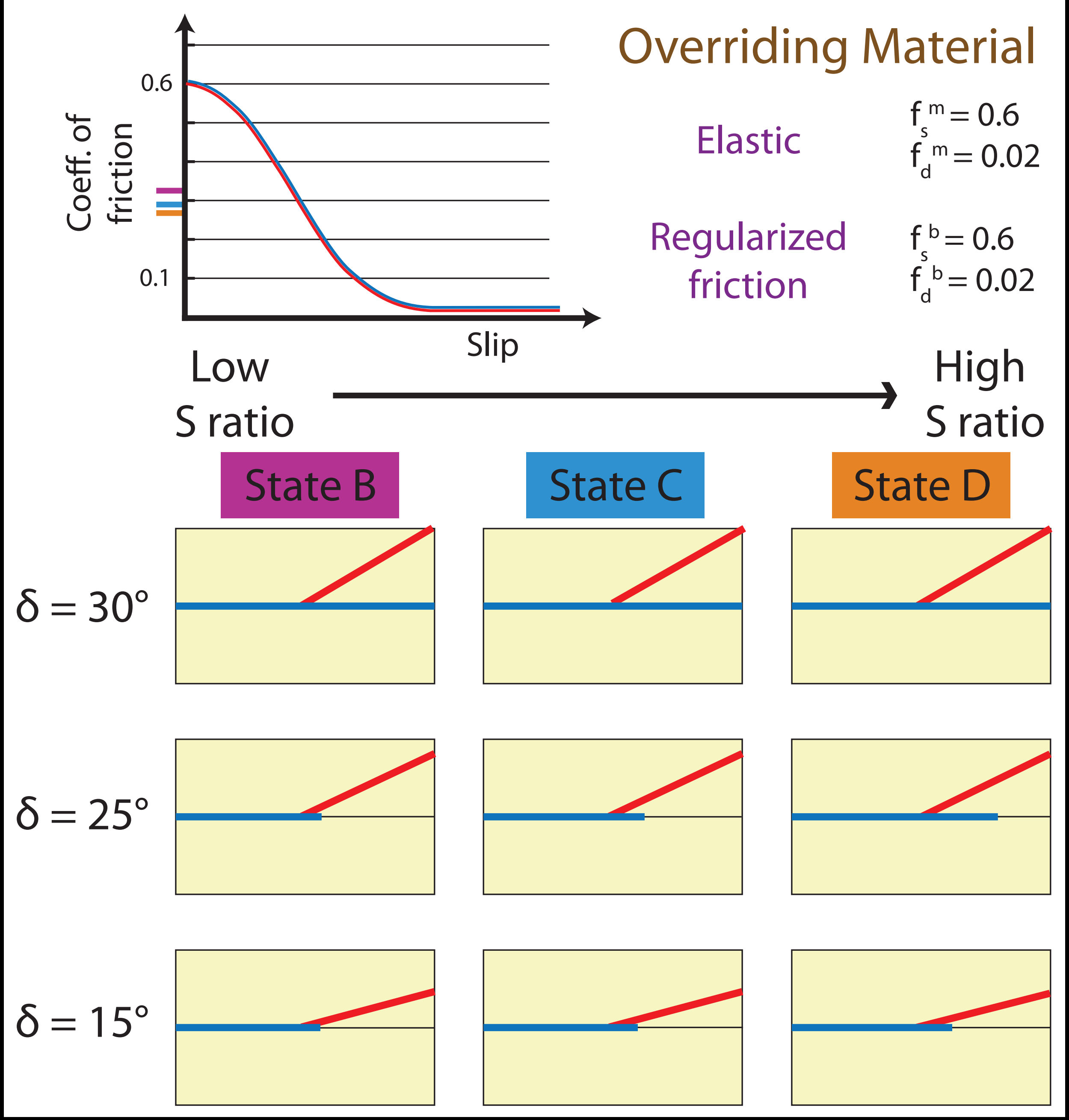




Dynamically Weak



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  $f_d^{main} < f_d^{branch}$

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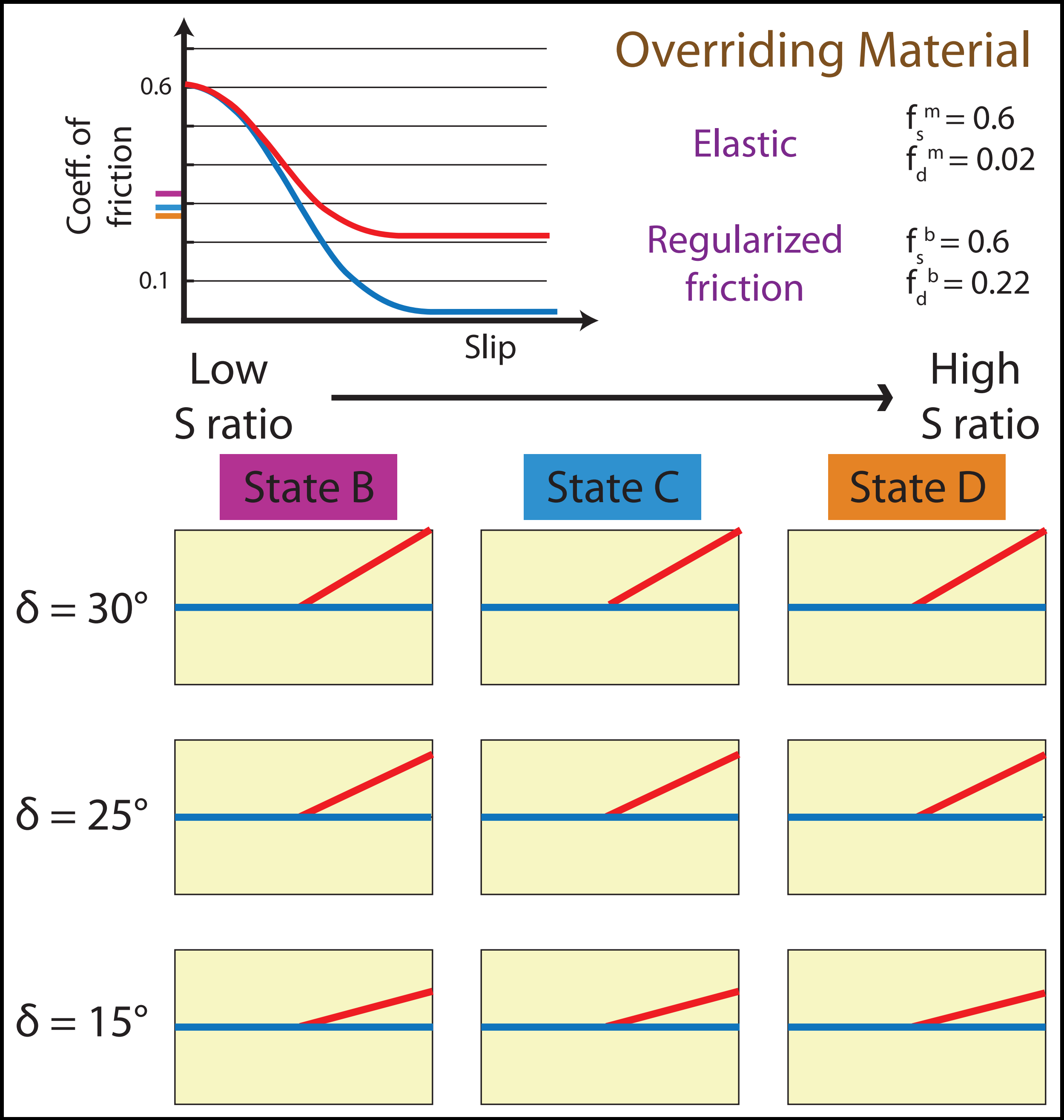


- Dynamically weak means that:

  $f_d^{main} < f_d^{branch}$

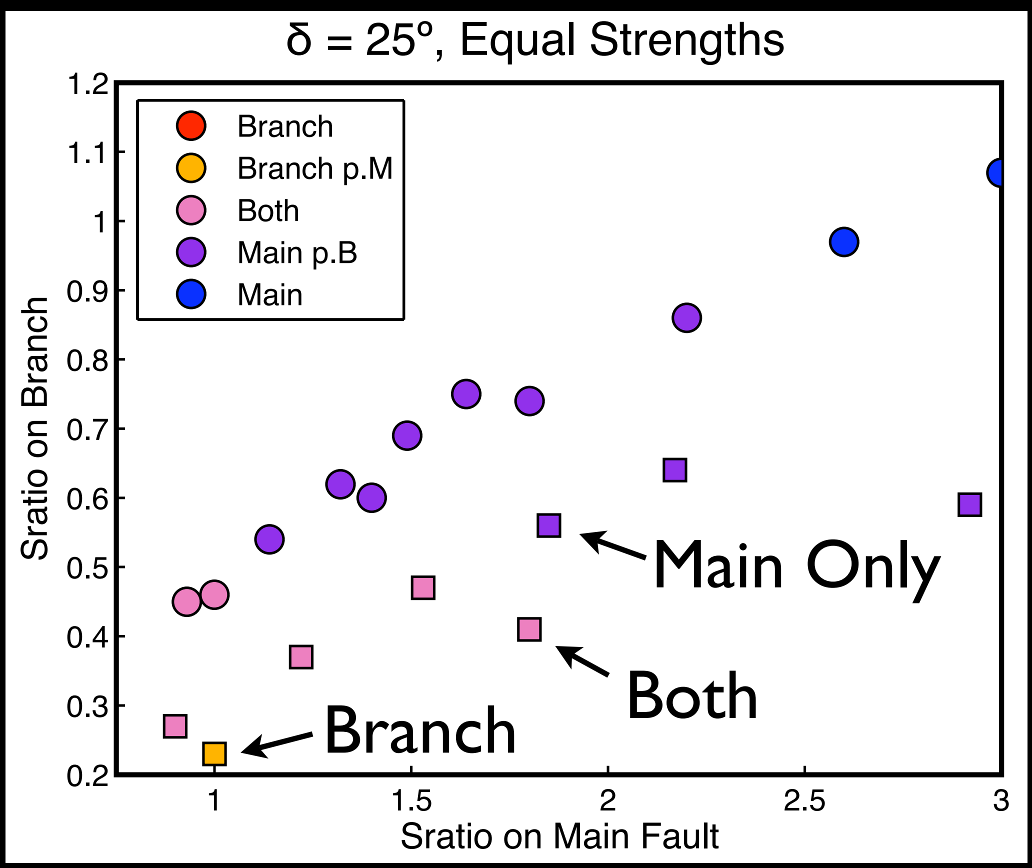
- $f_d^{branch} = 0.02, 0.22$

- No effect on branch activation.

- Basal rupture continuation is increased by a dynamically strong branch due to a smaller stresses drop on the branch and less of a stress shadow on the main fault

Effect of S Ratio?

- When strength contrasts exist between the two faults, the S ratio dependence disappears and the branch can be activated for higher S ratios



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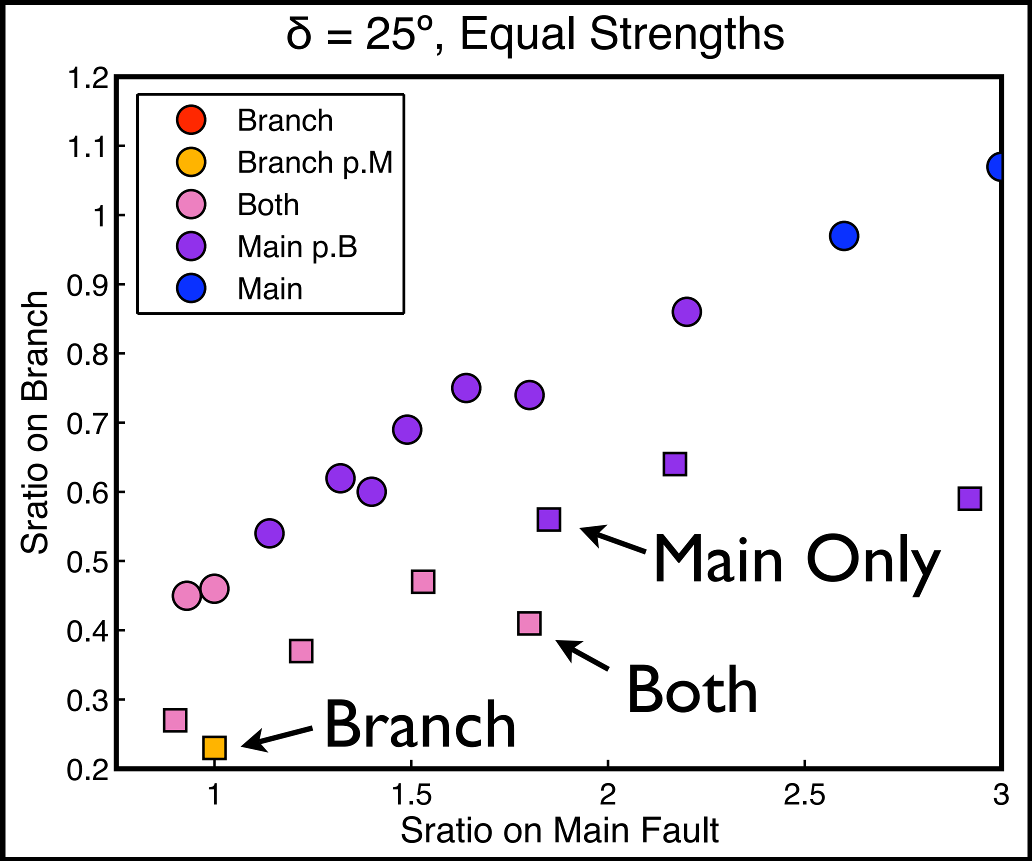
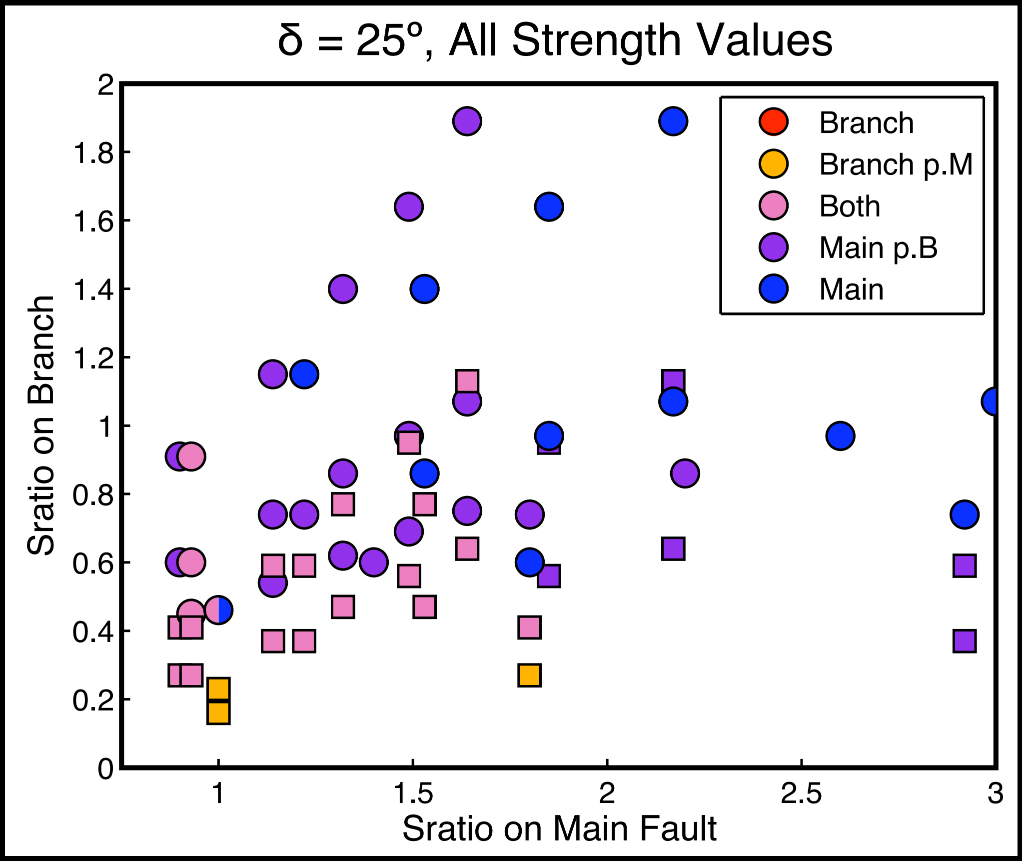
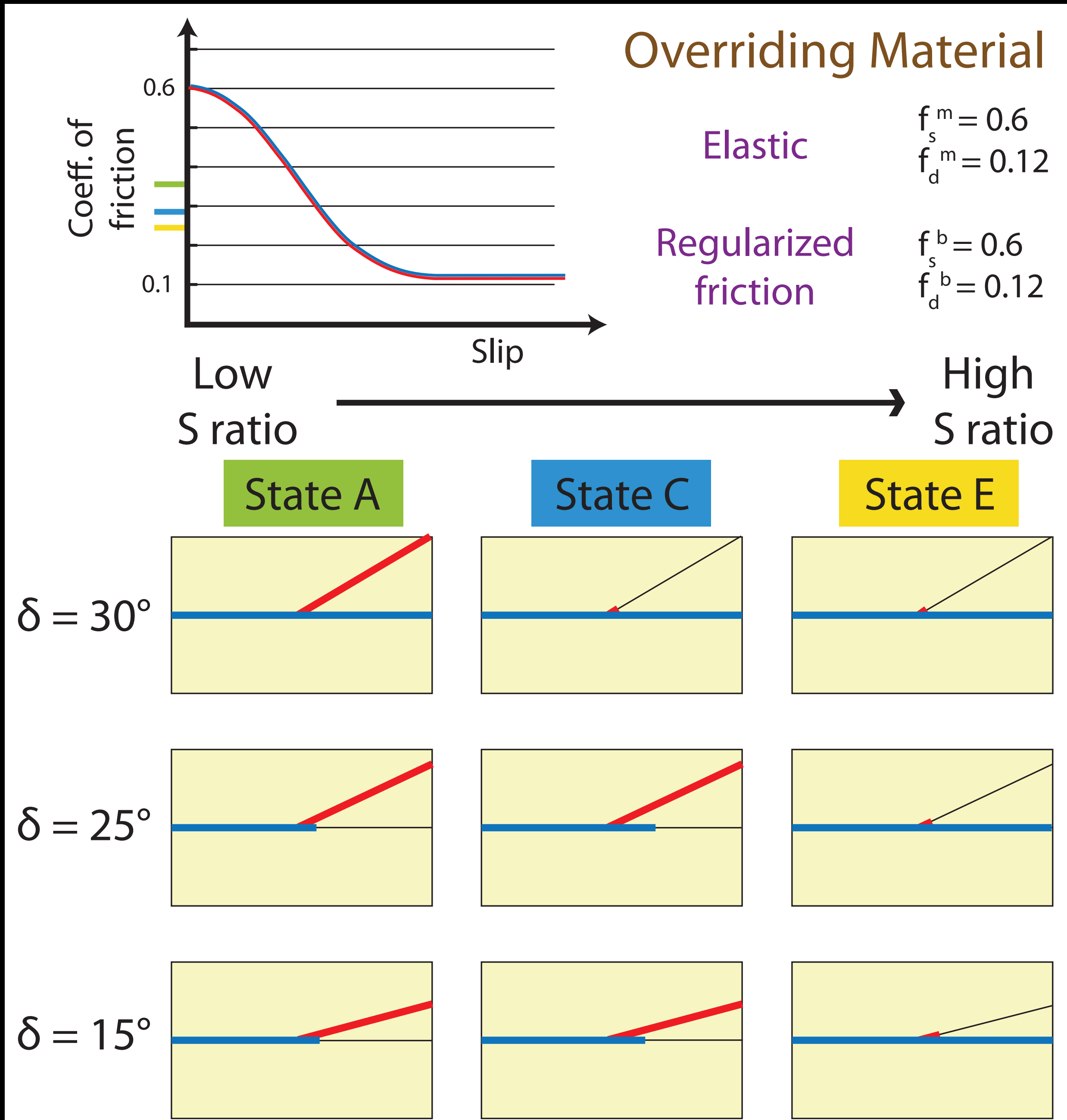




Bimaterial Branching



- The inclusion of a faster more rigid material leads to more branch activation
- Slip on the splay fault in the bimaterial model results in a larger area of the main fault falling under a stress shadow

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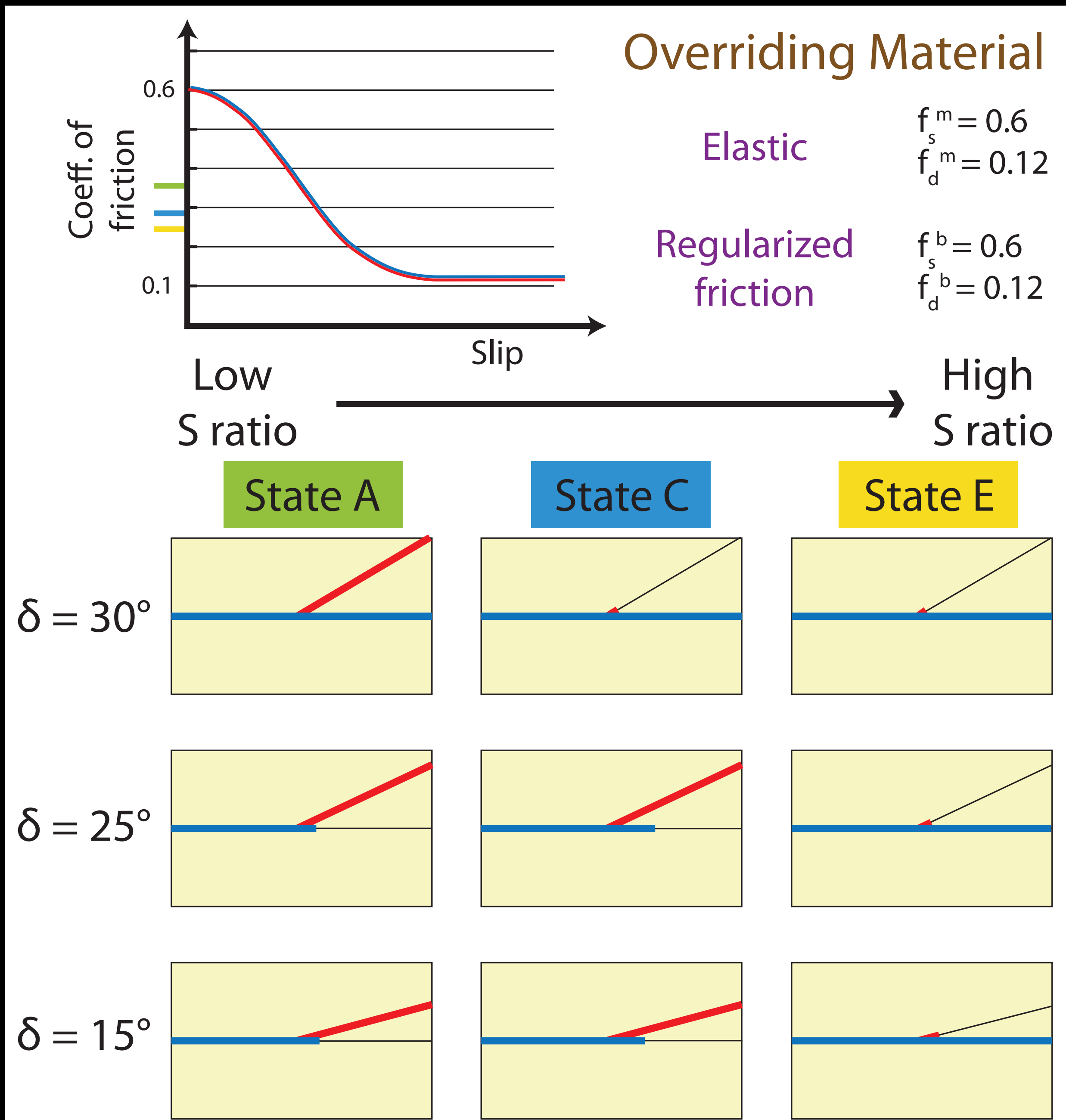

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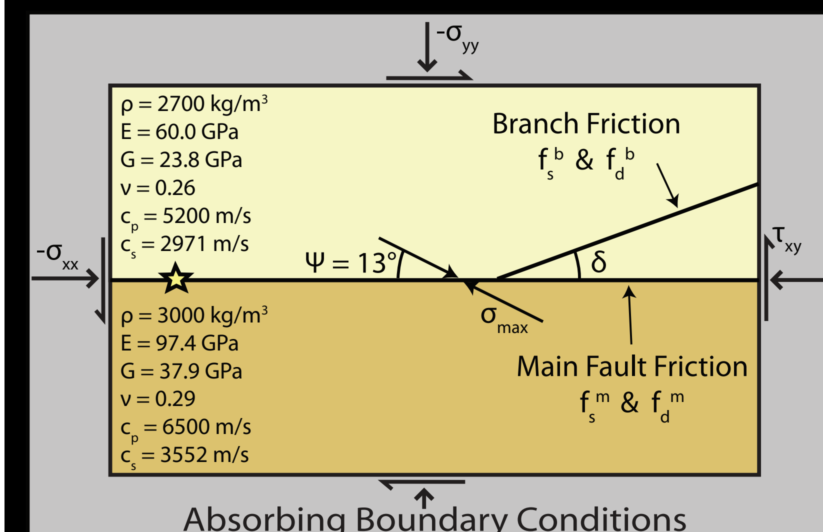

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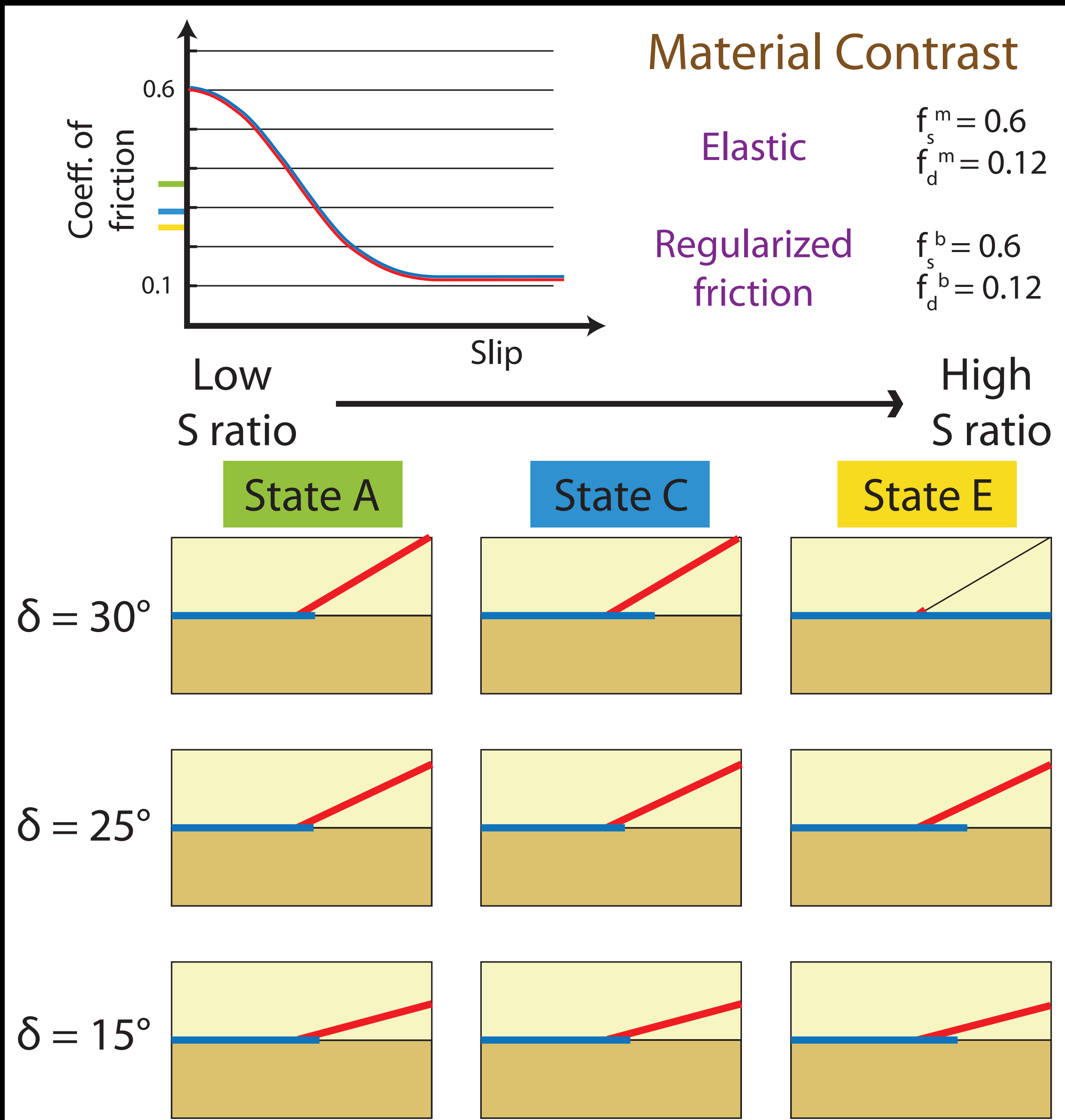

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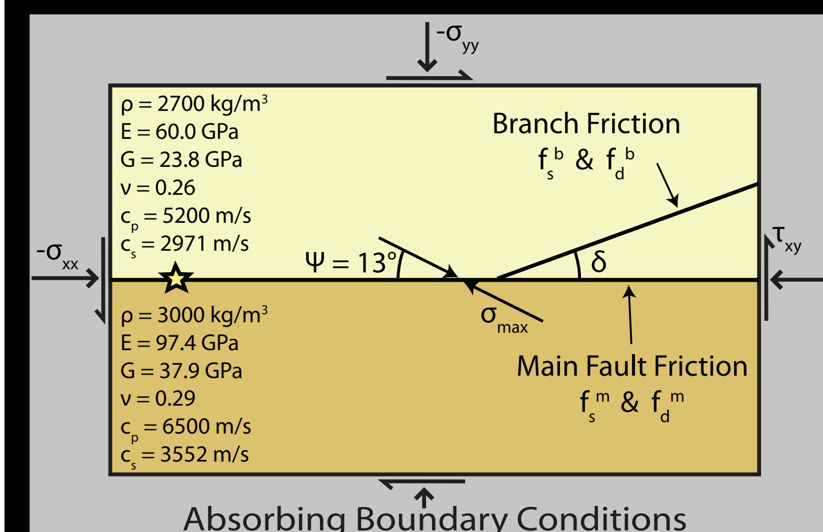
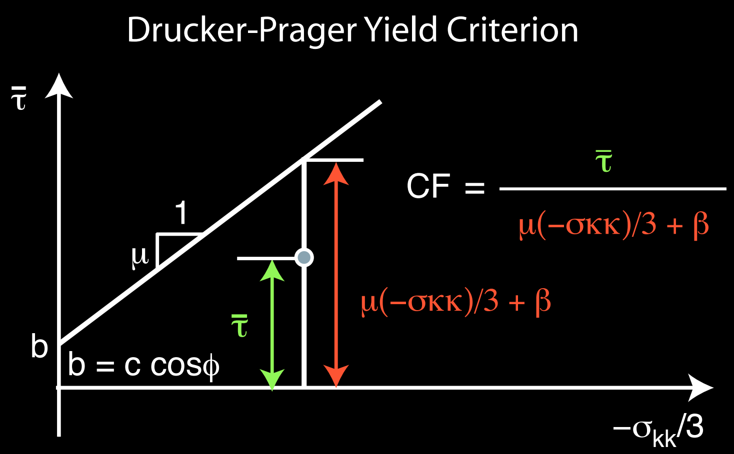
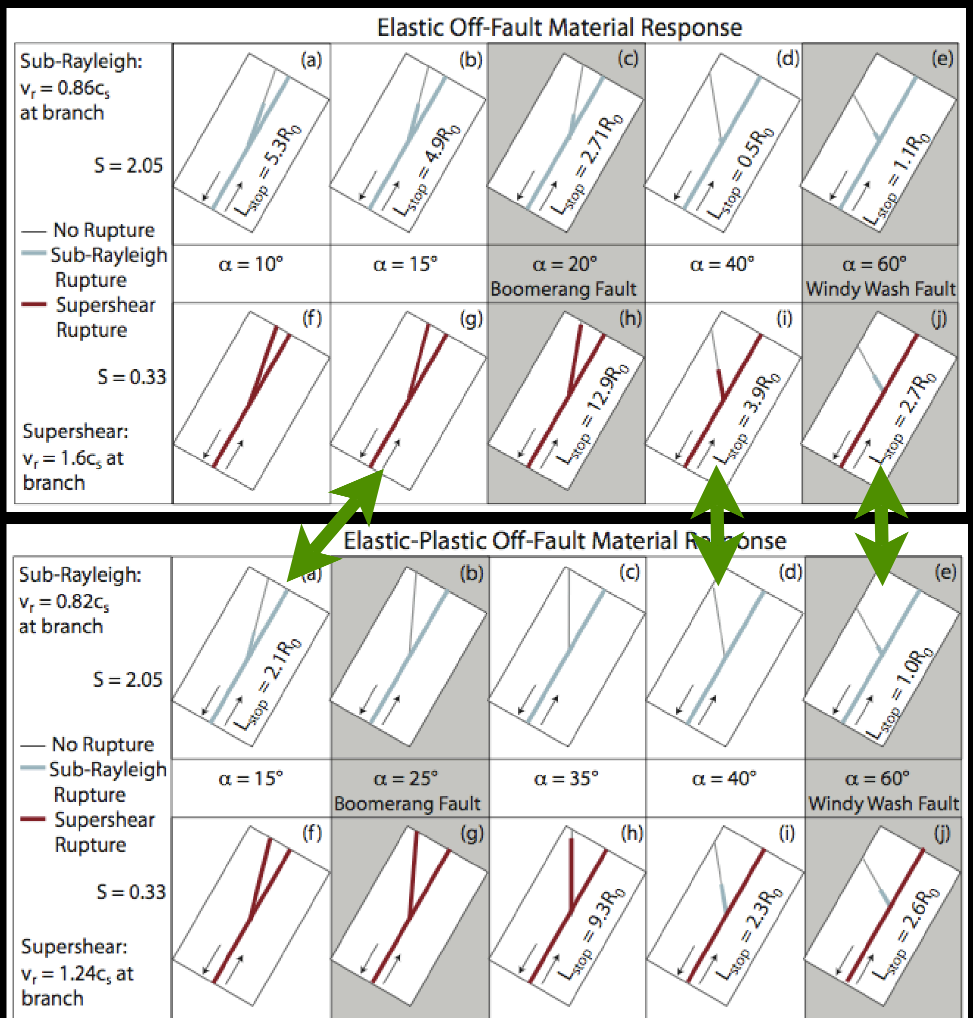




Normal Fault Branch Activation

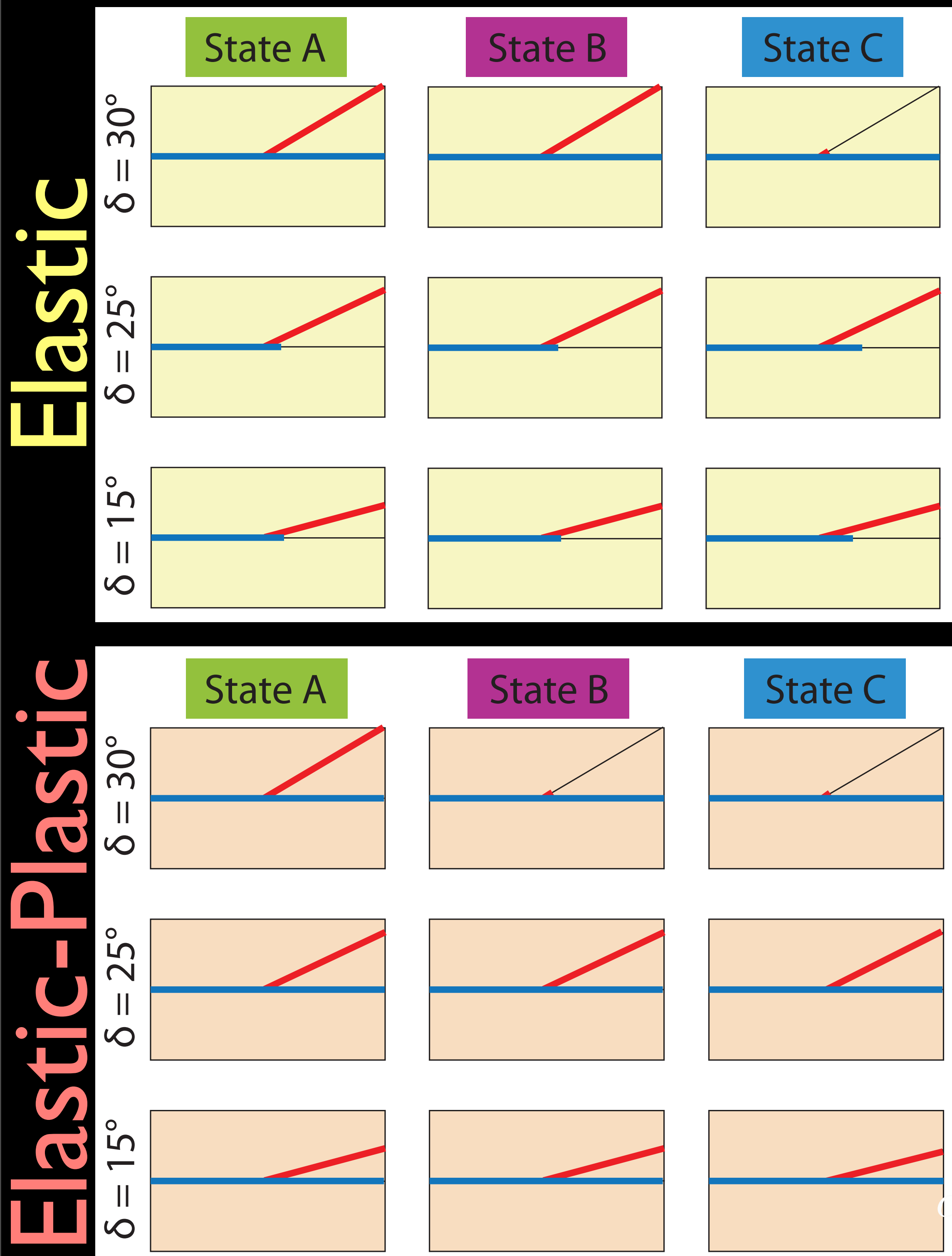


(Templeton et al., subm. BSSA 2009)

- Normal faulting environment near Yucca Mtn. requires supershear rupture speeds for branch fault activation.
- For this fault geometry, the inclusion of plastic deformation off the fault has little effect on the branch activation.

$$c = 0 \quad \mu = \tan 31^\circ \quad \beta = \frac{d\epsilon^{pl}}{d\gamma^{pl}} = \tan 24^\circ$$

Elastic- Plastic Behavior



- The addition of elastic-plastic off-fault deformation has little effect on the branch activation.
- The rupture propagation along the main fault is significantly changed and the likelihood of simultaneous activation is increased.

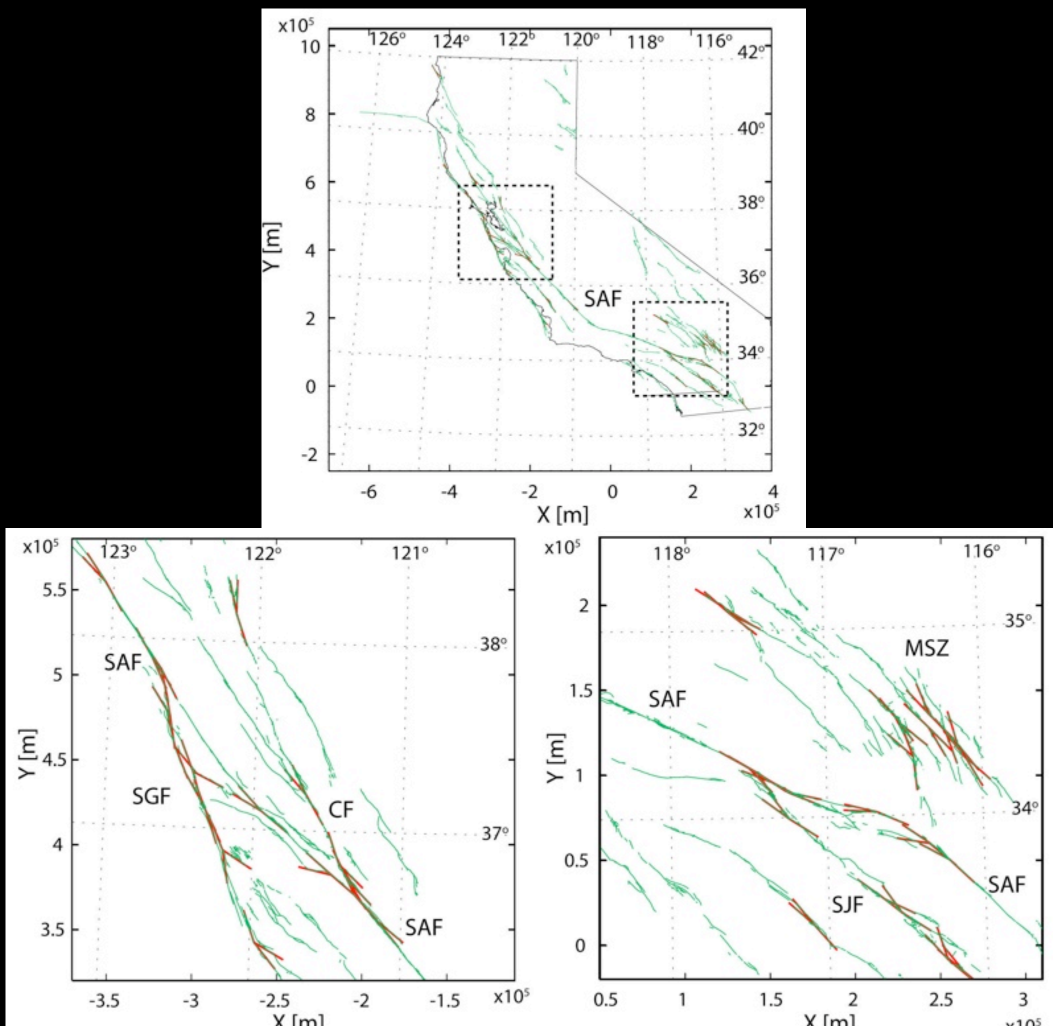
Note that the elastic-plastic ruptures do not use the regularized slip weakening law.

$$c = 0 \quad \mu = \tan 31^\circ \quad \beta = \frac{d\epsilon^{pl}}{d\gamma^{pl}} = \tan 24^\circ$$

Outline

- Branching theory and discussion of significant parameters
  - Rupture velocity
  - Principal stress orientation
  - Branch Geometry
- Modeling of recent branched rupture earthquakes
  - Buried faults
  - Backward Branching
  - Multiple earthquake cycles
  - Finite branches
- Recent work with Finite Element Modeling
  - Some subtleties of the branching point definition
  - Agreement with the laboratory and Wenchuan earthquake
  - Role of fault strength contrasts
  - Bimaterial effects
  - Effects of including plasticity
- Branch formation and quantifying existing fault geometries

Quantifying Natural Fault Geometries



(Ando et al., BSSA 2009)

- Using available fault surface data, what geometries are most commonly observed?
- Fit a Y of arbitrary shape to surface fault traces.
- Change the length of the Y branches to assess the length scale dependence of the result

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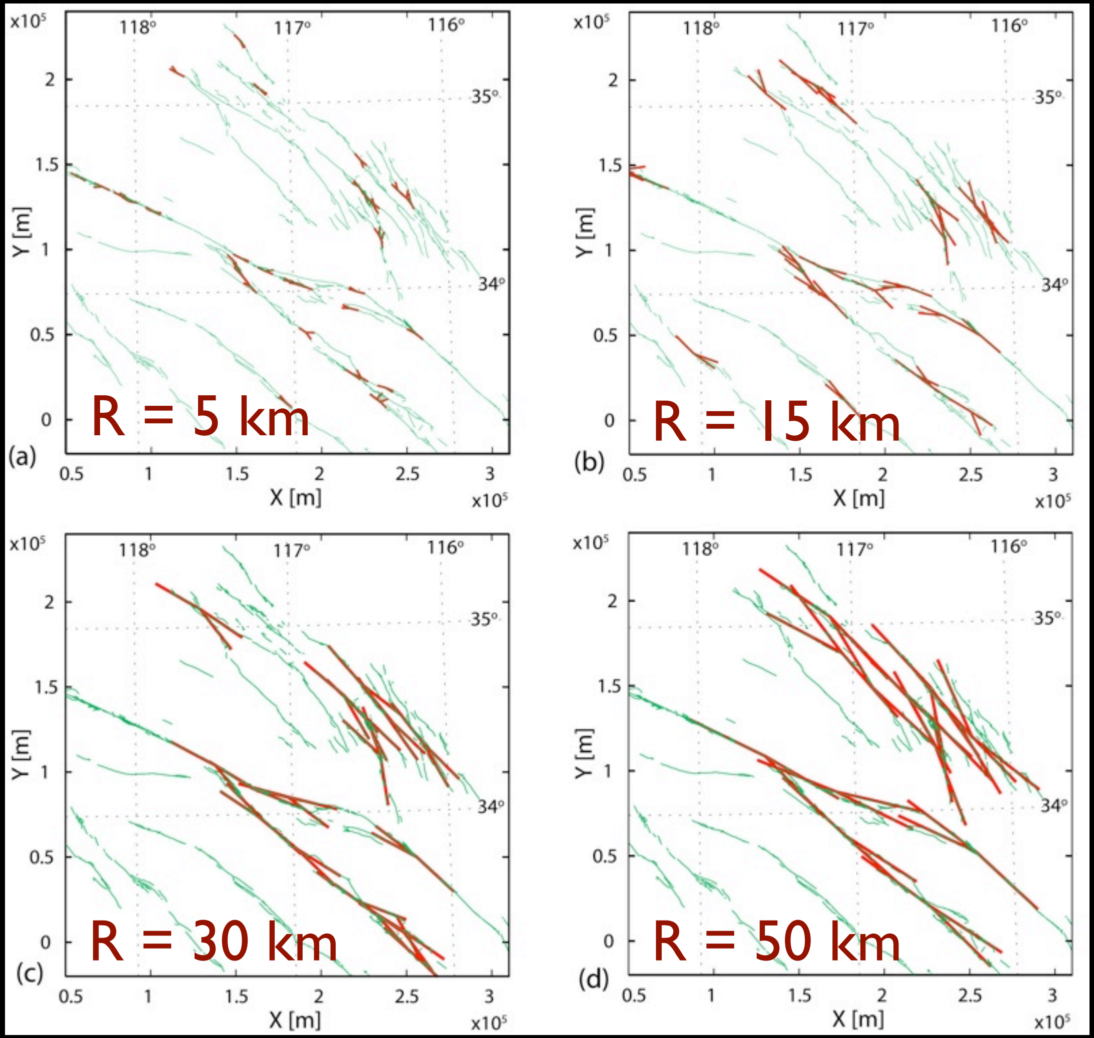

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- Using available fault surface data, what geometries are most commonly observed?
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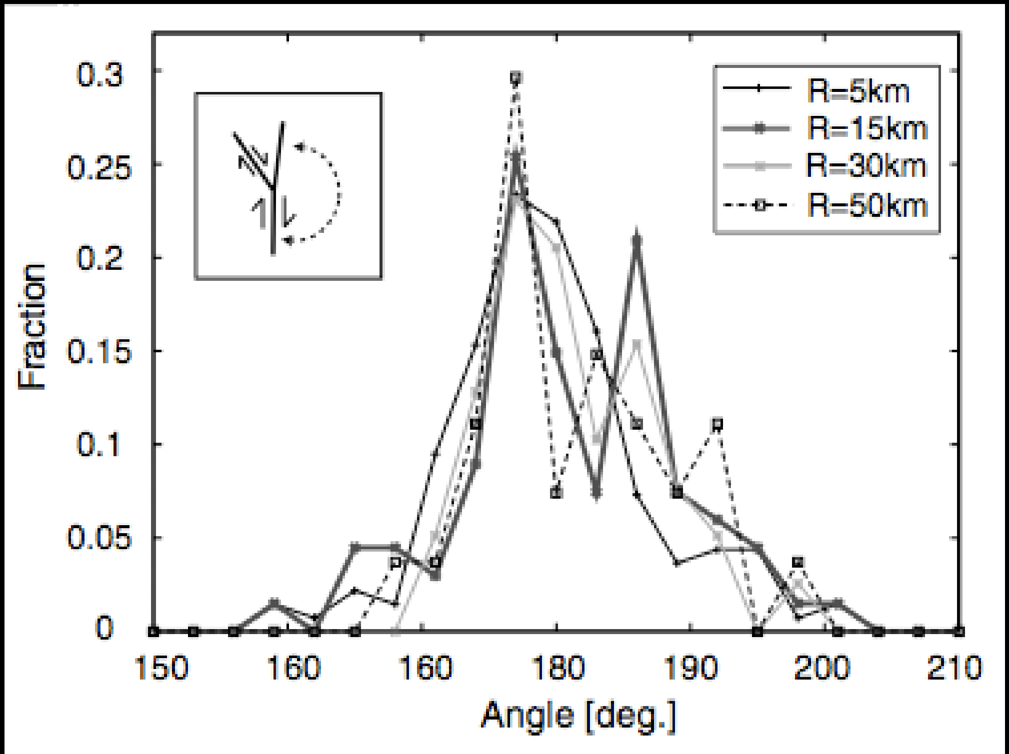
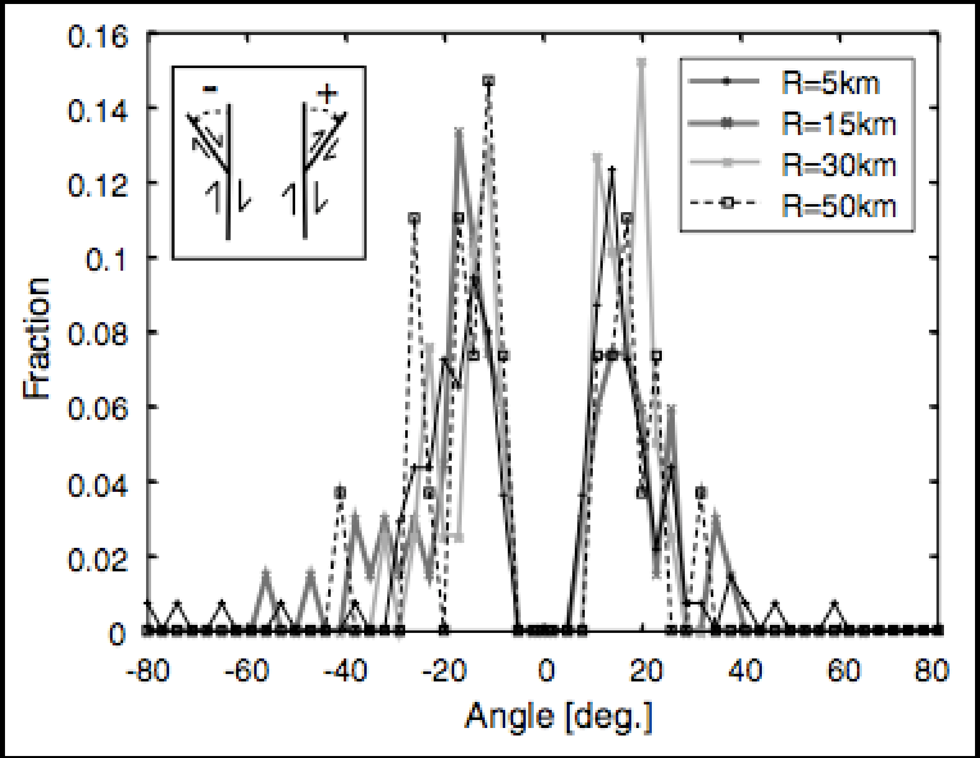
Dominant Geometries

- Y-like branches are rare geometries in natural fault systems.
- Splay fault distributions center around ±17°
- This result is independent of length scale.

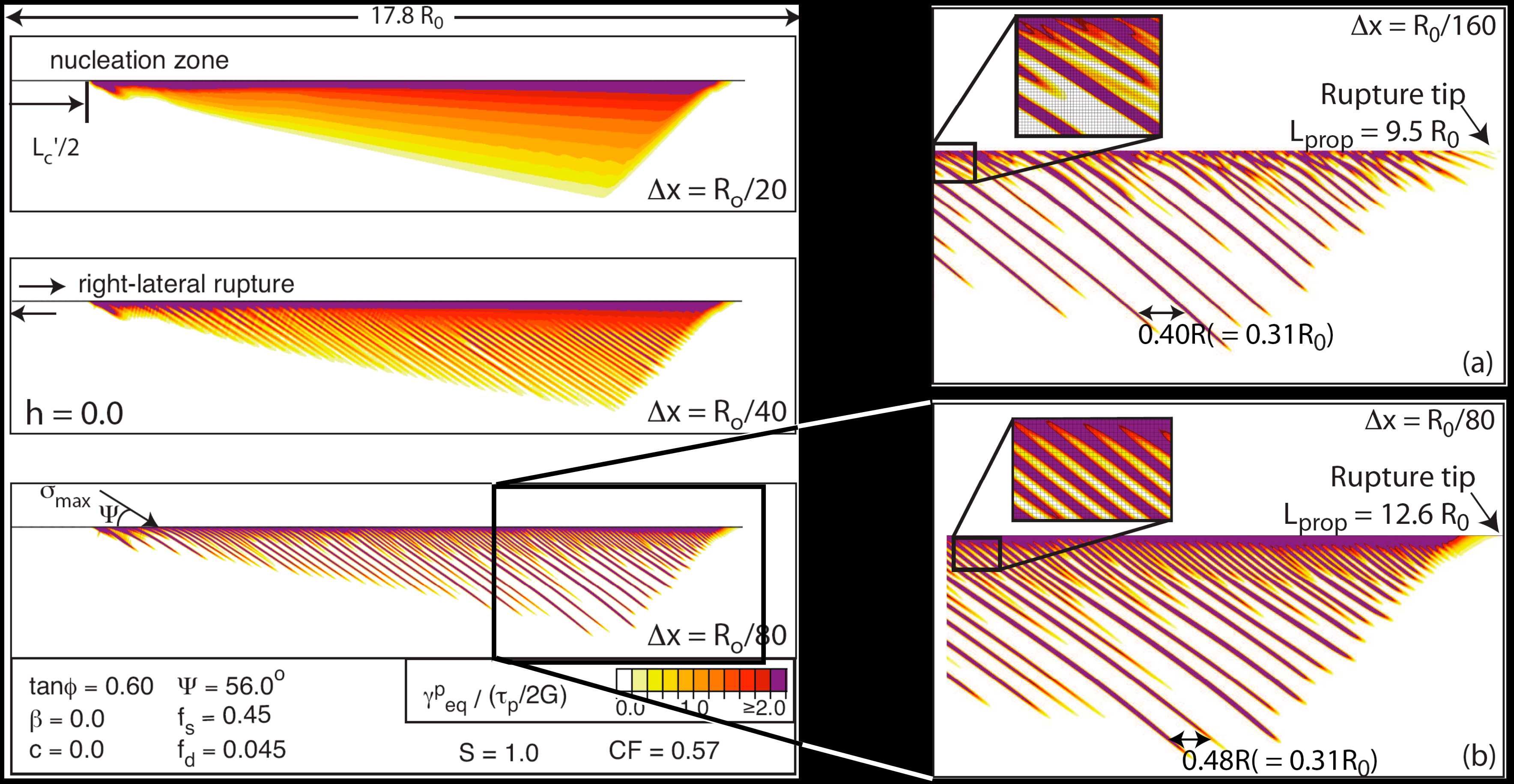


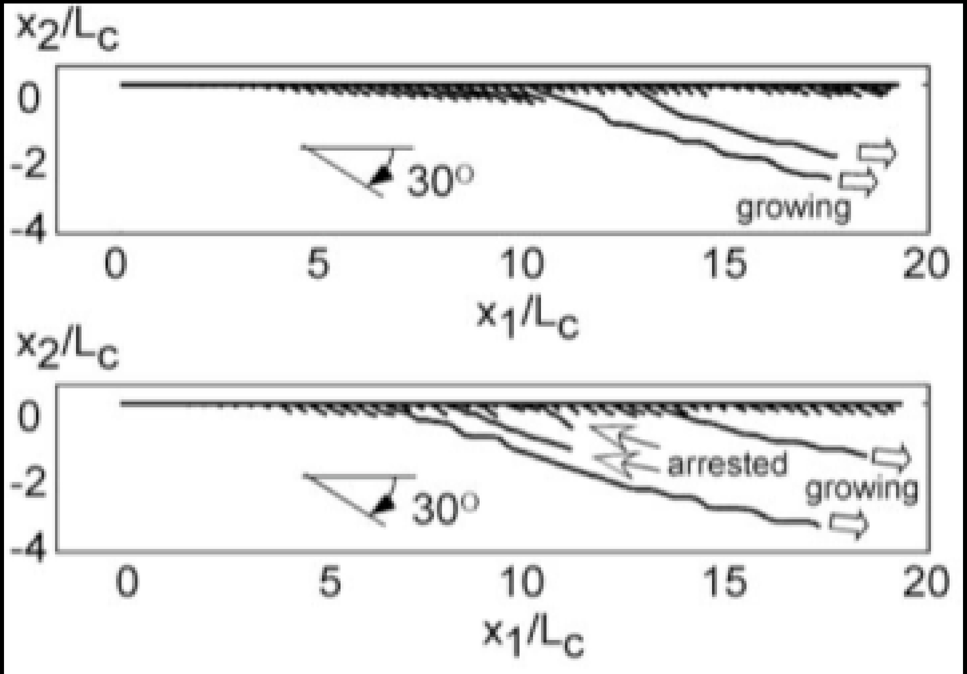


(Ando et al., BSSA 2009)

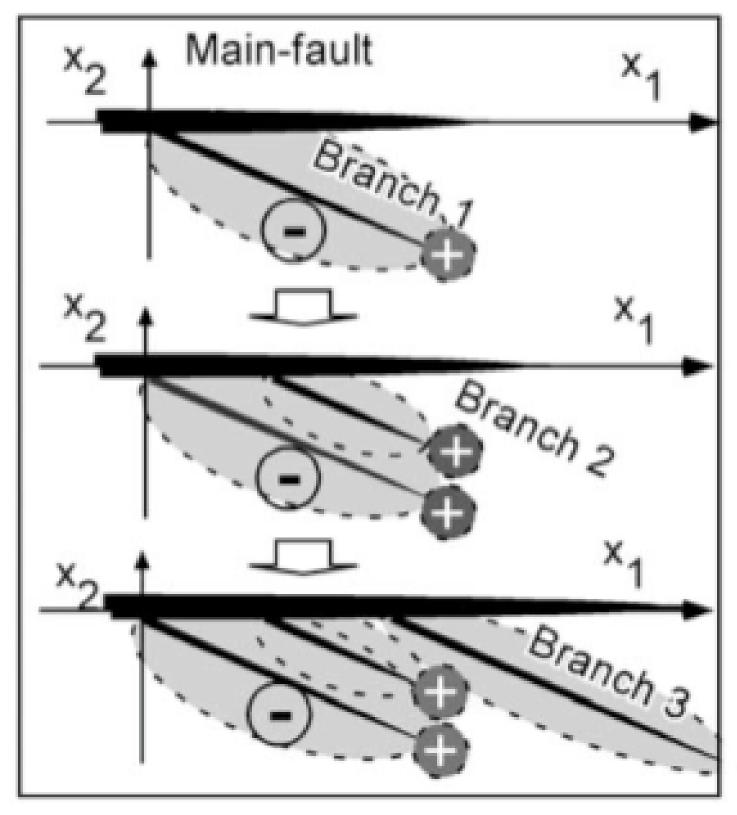
Off-Fault Strain Localizations

- When the hardening is less than a critical value, strain localizations develop which may be precursors to persistent branch formation.
- Aperiodic localization features have an average spacing that is grid independent and scales with a real length scale.





Spontaneous Growth of Branches



(Ando & Yamashita, JGR 2007)

- Each branch tip extends in the direction of maximum shear traction.
- The size of the small branches is determined by the size of the stress enhancement zone due to the rupture tip.
- The growth of a large scale branch suppresses the growth of the nearby branches due to a stress shadow.

Modeling Considerations

- Branch Geometry
- Stress Orientation: Ψ and σ_1/σ_3
- Rupture Velocity / Nucleation Location
- Mesh Definition at the Branching Point
- Fault Intersections
- Length of the Branch
- Relative Fault Strengths
- Blind Rupture
- Elastic Plastic Response