Conference on ***Friction, Fracture and Earthquake Physics***,
Kavli Institute for Theoretical Physics, Santa Barbara, 15-19 August 2005

Dynamics of rupture through branched and offset fault systems

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Questions

- How the earthquake rupture chooses its path through geometric complexities like bends, branches and stepovers? When and why a fault branch might be preferred? Would the rupture continue as well along the main fault?

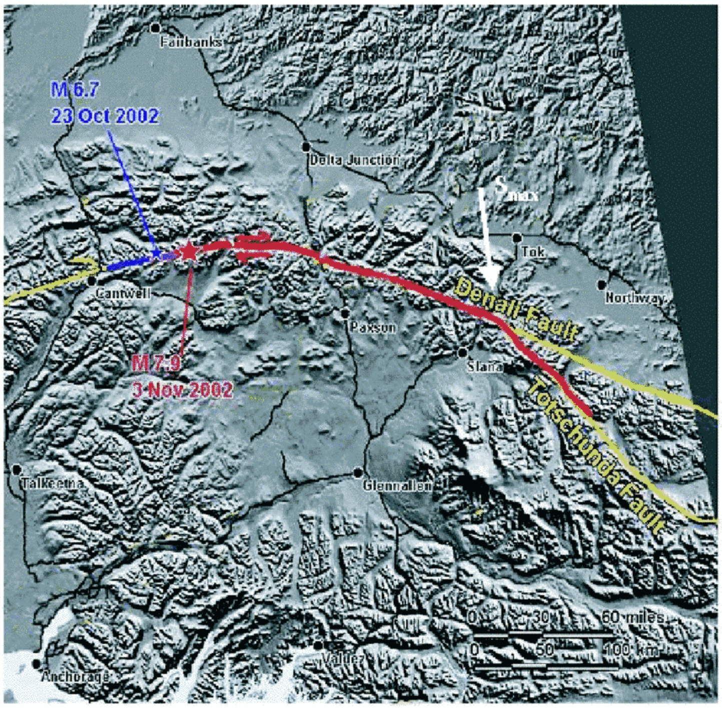
- Could the directivity of a complex earthquake be inferred from a pattern of fault branches it ruptured?

- How do small fault branches interact with the main rupture propagation? Could they arrest rupture? How they contribute to seismic radiation?

- What is the off-fault damage pattern related to supershear (versus sub-Rayleigh) rupture propagation?

- Can laboratory experiments be used to constrain branching theory?

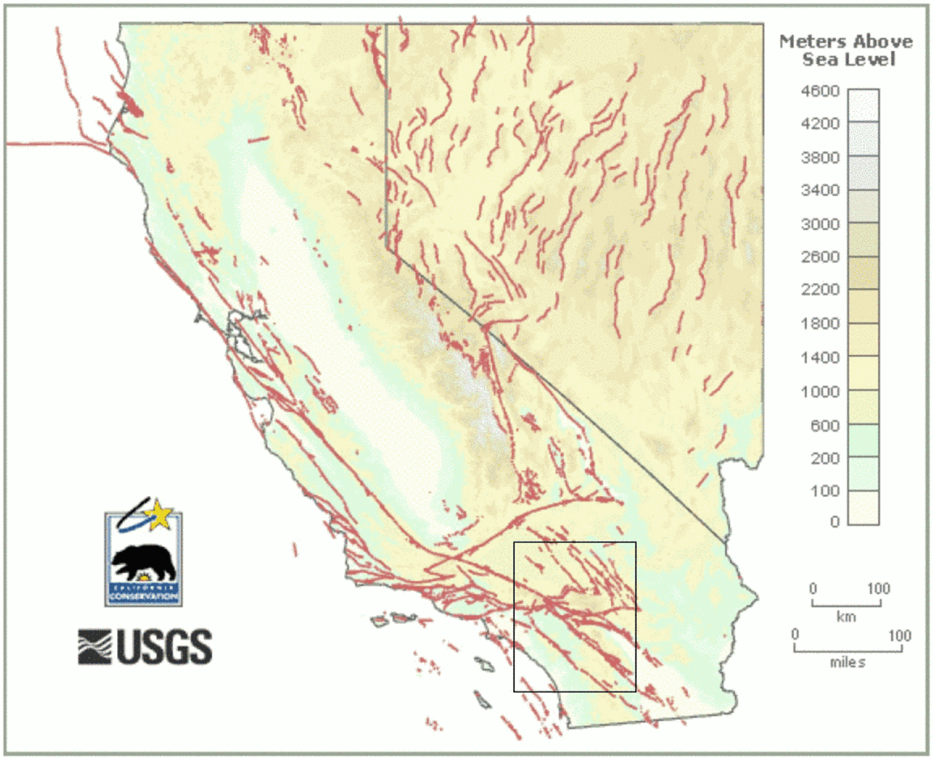
M_w 7.9 Denali Earthquake, 3 Nov 2002



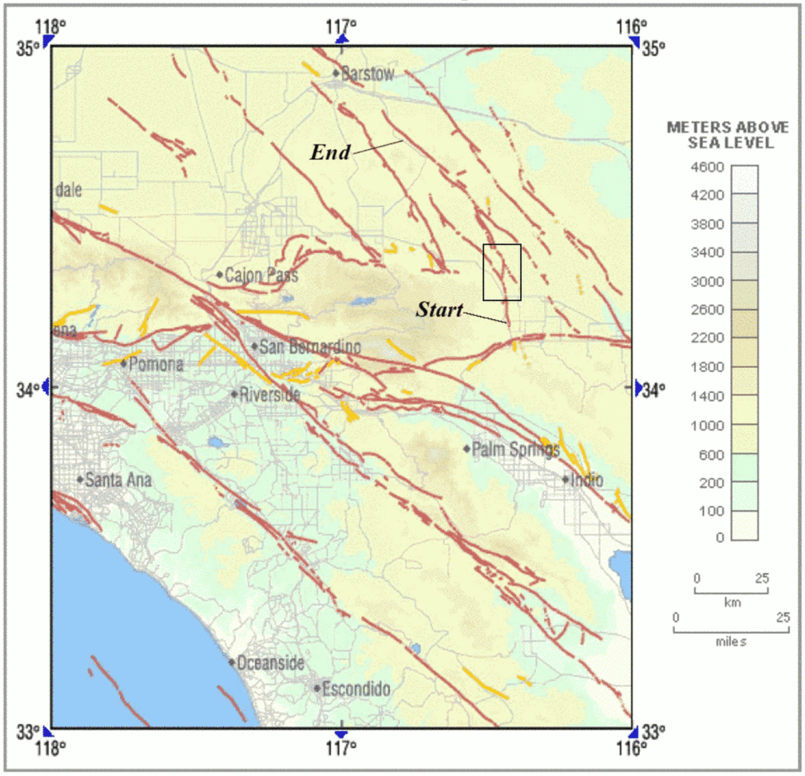
Map provided by
P. Haeussler, *USGS Fairbanks*, 2002

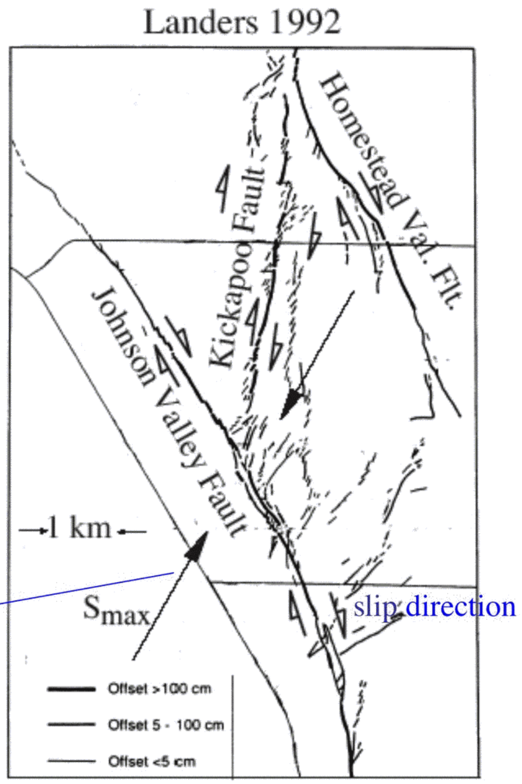
Stress direction at branch junction (white arrow) from Ratchkovski and Hansen (2002) and earlier studies.

California and Nevada -- active faults (from USGS)



Faults in Southern California, Mohave Area (from USGS)
***Start* and *End* of 1992 Landers rupture shown**





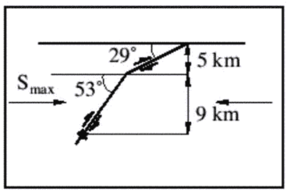
Portion of 1992 Landers earthquake rupture path (transition from Johnson Valley to Kickapoo fault, then to Homestead Valley fault).

Fault map and slip, Sowers et al. (1994).

Pre-stress direction, Hardebeck and Hauksson (2001).

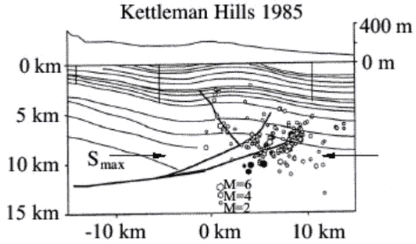
(Poliakov, Dmowska and Rice, *JGR*, 2002; Kame, Rice and Dmowska, *JGR*, 2003)

San Fernando 1971



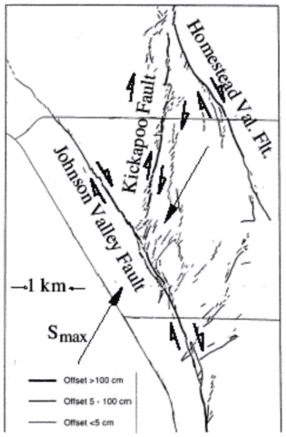
(Heaton and Helmberger, 1979)

Kettleman Hills 1985



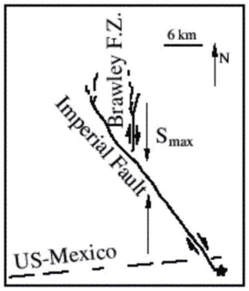
(Ekstrom et al., 1992; fault locations from Meltzer, 1989)

Landers 1992



(fault map from Sowers et al., 1994; stress from Hardebeck and Hauksson, 2001)

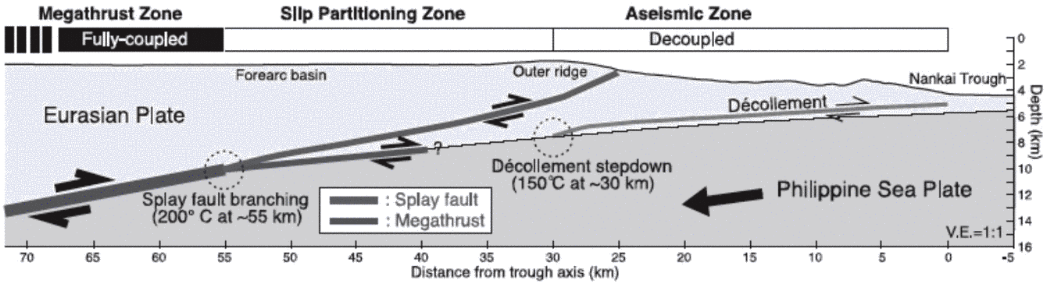
Imperial Valley 1979



(Archuleta, 1984; stress guessed from Hardebeck and Hauksson, 1999, to NW)

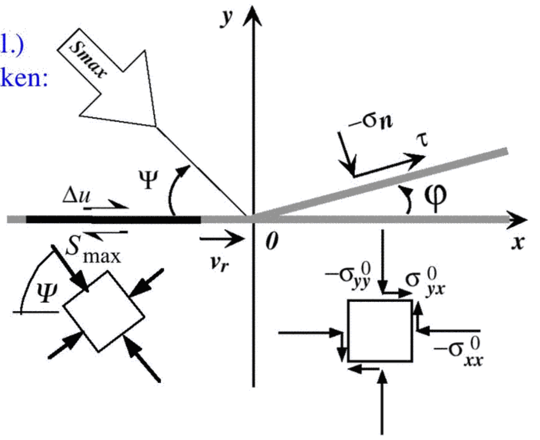
Nankai Trough, area of 1944 Mw 8.1 Tonankai earthquake (Park et al., *Sci*., 2002; Nakanishi et al., *JGR*, 2002)

Splay fault branching. Relation to tsunami generation?



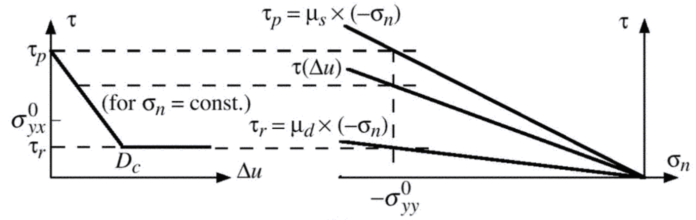
Theory and computational modeling (Poliakov et al., *JGR*, 2002; Kame et al., *JGR*, 2003)

Parameters argued (Poliakov et al.) to control whether branch path taken:
φ -- branch angle
Ψ -- direction of max. pre-stress
v_r -- rupture speed at junction



(a)

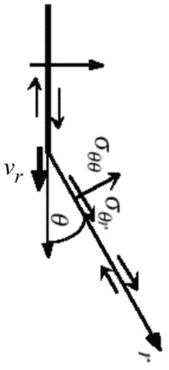
Slip-weakening model of frictional failure (Kame et al.);
τ = shear stress,
σ_n = normal stress,
Δu = fault slip.

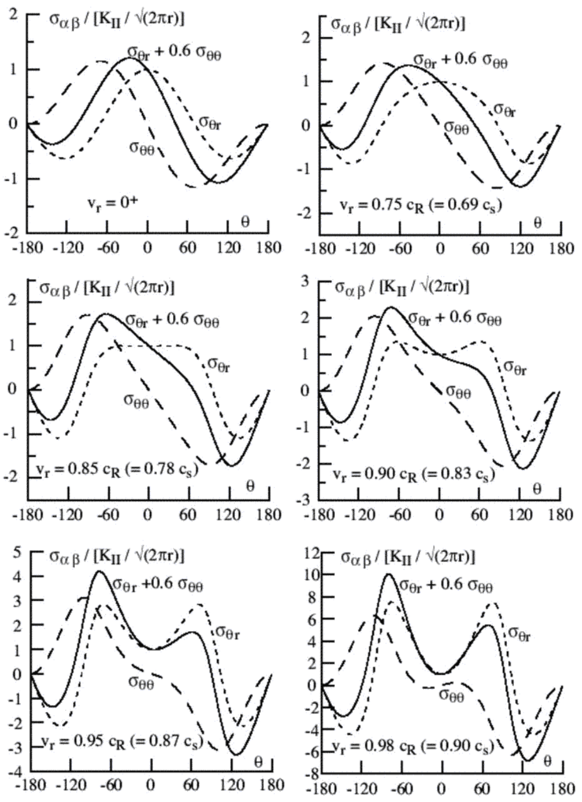


(b)

Perspective from singular elastic crack theory on the expected importance of *rupture propagation speed* v_r at the branch junction (Poliakov et al., *JGR*, 2002)

Plotted:
Singular $1/\sqrt{r}$ stress terms, normalized by $K_{II}/\sqrt{(2\pi r)}$ $(=\sigma_{\theta r}|_{\theta=0})$, for various rupture speeds v_r .



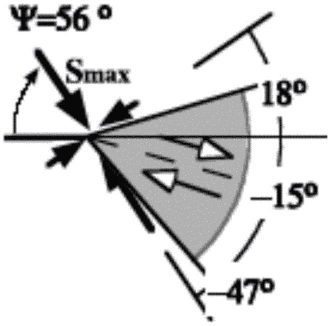


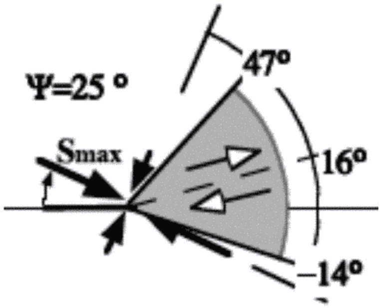
(Poliakov et al., *JGR,* 2002; Kame et al., *JGR,* 2003)

Once initiated in the high stress region, can a branched rupture become large?

Importance of direction Ψ of maximum principal compression in pre-stress field

steep pre-stress angle
favors extensional side





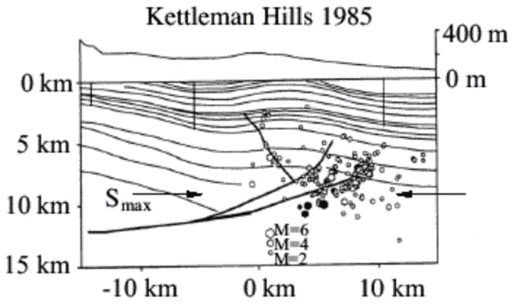
shallow pre-stress angle
favors compressional side

Dashed lines: Directions of maximum $\tau^{0} / (-\sigma_n^{0})$
Shaded regions: Sectors where $\tau^{0} / (-\sigma_n^{0}) > \mu_d$ (= *dynamic friction coef.*)

(Poliakov, Dmowska and Rice, *JGR*, 2002)

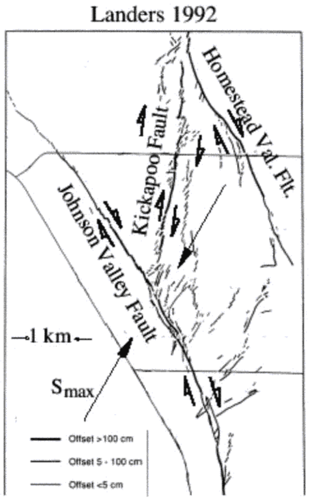
Correlation with natural examples

Depth cross-section view: Shallow S_{max} direction, $\Psi \approx$ 12-18°; secondary failures on *compressional* side:



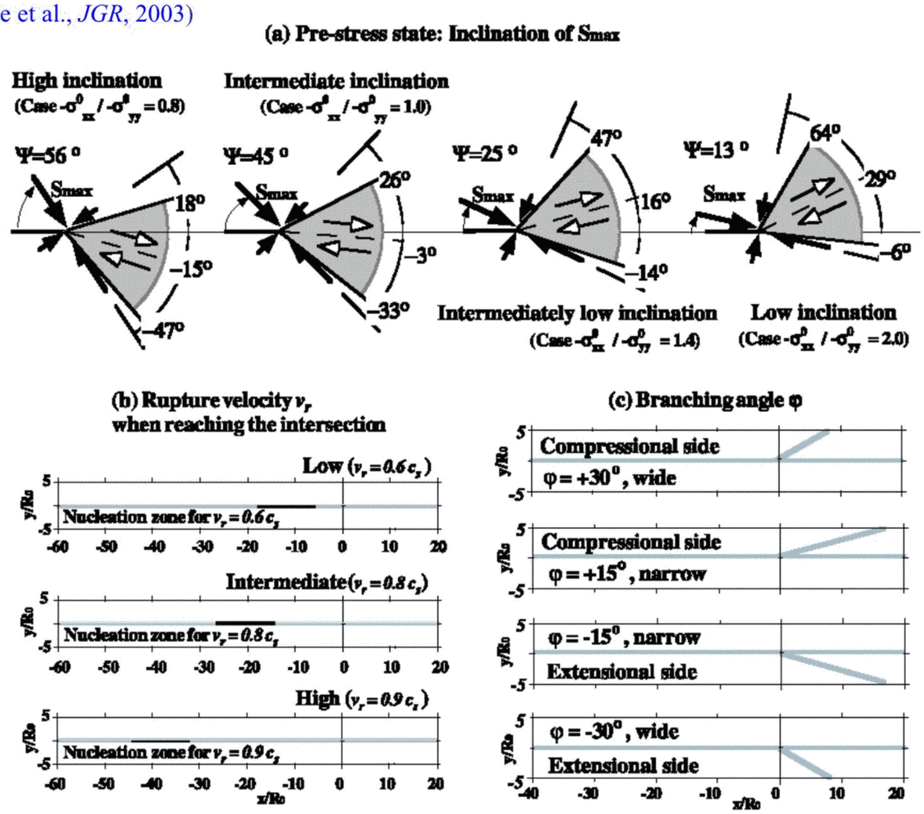
(Ekstrom et al., 1992; fault locations from Meltzer, 1989)

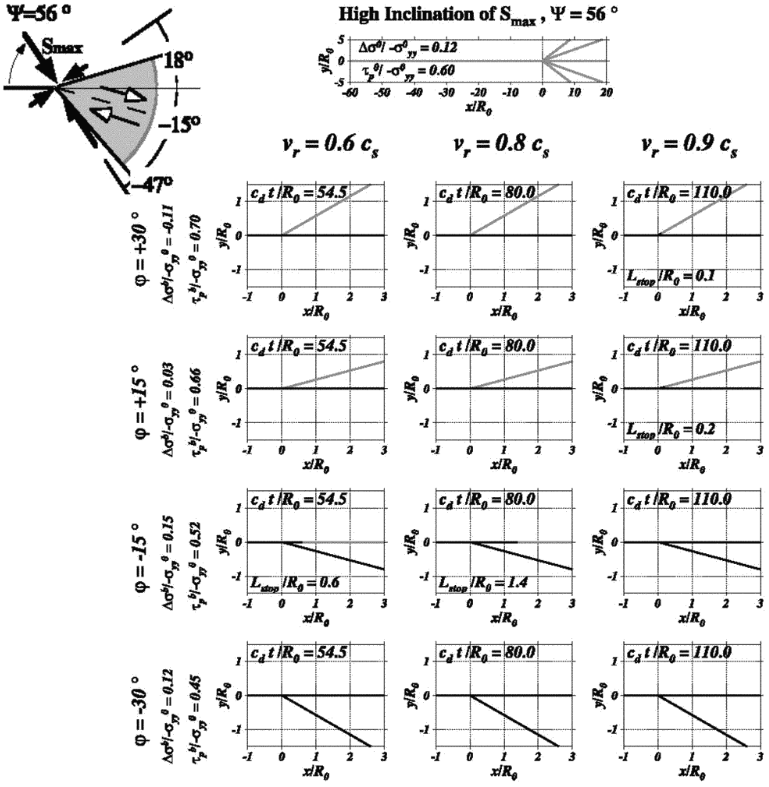
Map view: Steep S_{max} direction, $\Psi \approx 60°$; secondary failures on *extensional* side:

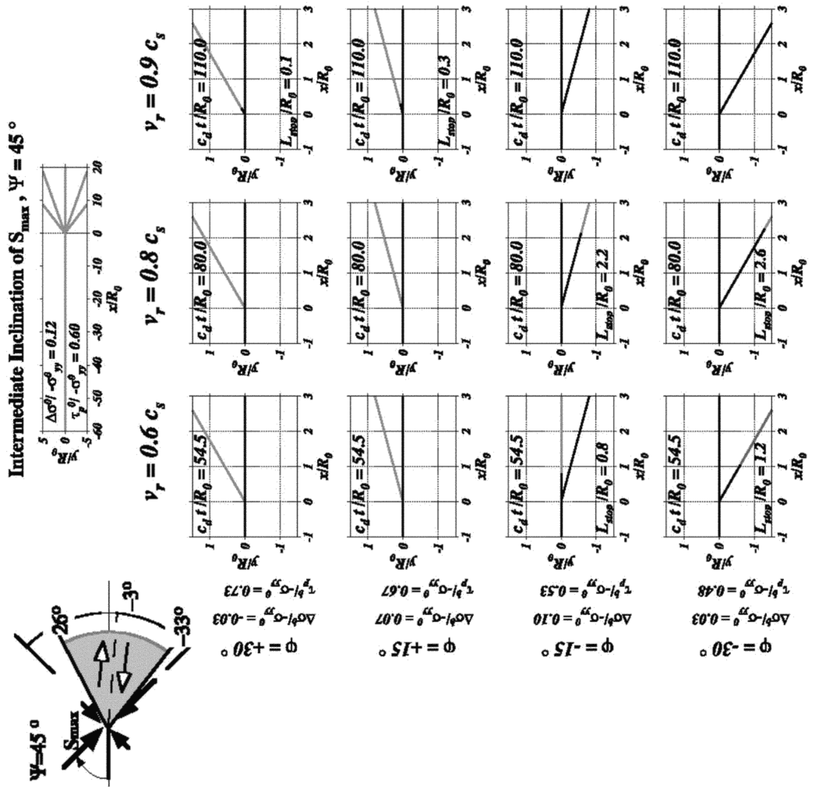


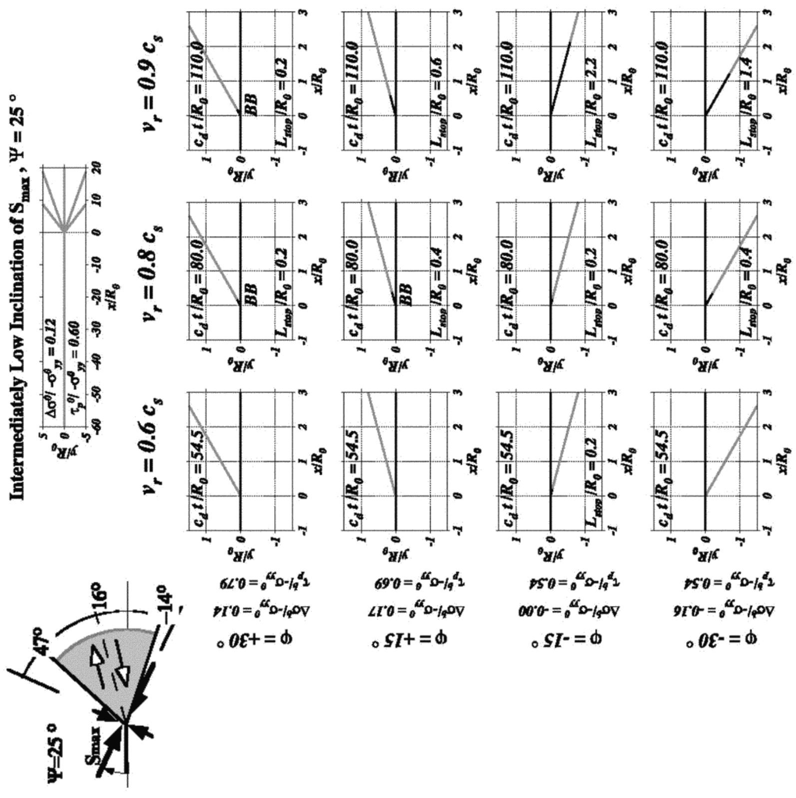
(fault map from Sowers et al., 1994;
stress from Hardebeck and Hauksson, 2001)

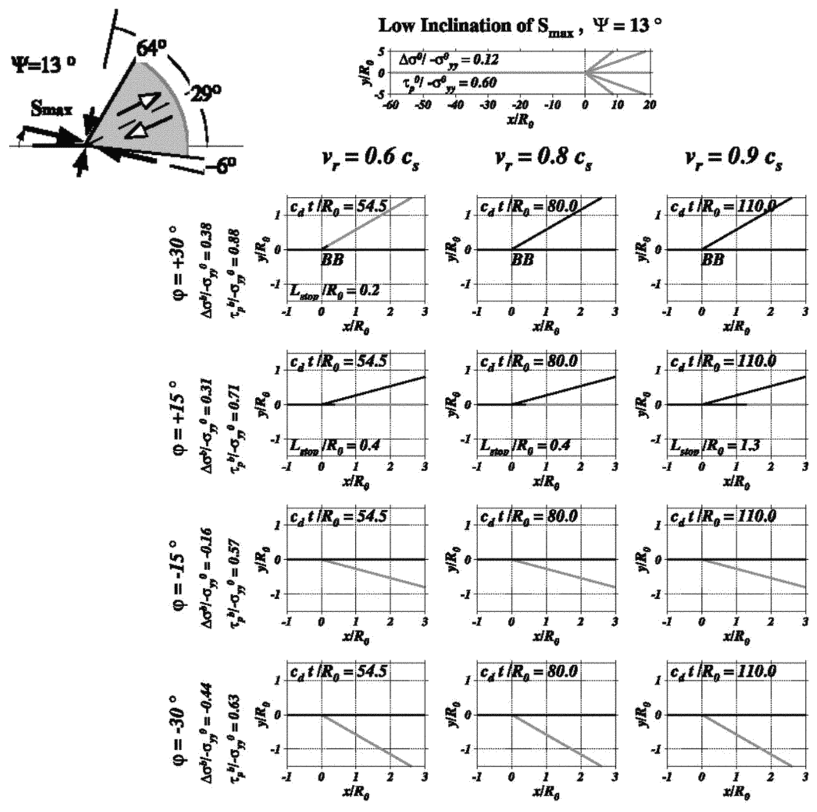
(Kame et al., *JGR*, 2003)





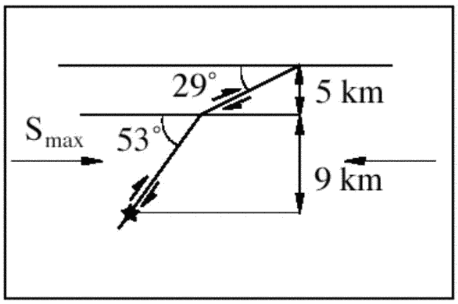

Intermediate Inclination of S_{max} , $\Psi = 45°$
$\Delta\sigma^0 / -\sigma^0_{yy} = 0.12$
$\tau_p^0 / -\sigma^0_{yy} = 0.60$
$v_r = 0.6\ c_s$
$v_r = 0.8\ c_s$
$v_r = 0.9\ c_s$
$c_d\ t / R_0 = 54.5$
$c_d\ t / R_0 = 80.0$
$c_d\ t / R_0 = 110.0$
$L_{stop} / R_0 = 0.1$
$L_{stop} / R_0 = 0.3$
$L_{stop} / R_0 = 0.8$
$L_{stop} / R_0 = 2.2$
$L_{stop} / R_0 = 1.2$
$L_{stop} / R_0 = 2.6$
x/R_0
y/R_0
$\phi = +30°$ $\Delta\sigma / -\sigma_{xx}^0 = -0.03$ $\tau_p / -\sigma_{xx}^0 = 0.73$
$\phi = +15°$ $\Delta\sigma / -\sigma_{xx}^0 = 0.07$ $\tau_p / -\sigma_{xx}^0 = 0.67$
$\phi = -15°$ $\Delta\sigma / -\sigma_{xx}^0 = 0.10$ $\tau_p / -\sigma_{xx}^0 = 0.53$
$\phi = -30°$ $\Delta\sigma / -\sigma_{xx}^0 = 0.03$ $\tau_p / -\sigma_{xx}^0 = 0.48$
26°
-3°
-33°
$\Psi = 45°$
S_{max}


Intermediately Low Inclination of S_{max} , $\Psi = 25°$
$\Delta\sigma^0 / -\sigma^0_{yy} = 0.12$
$\tau_p^0 / -\sigma^0_{yy} = 0.60$
$v_r = 0.6\ c_s$
$v_r = 0.8\ c_s$
$v_r = 0.9\ c_s$
$c_d\ t / R_0 = 54.5$
$c_d\ t / R_0 = 80.0$
$c_d\ t / R_0 = 110.0$
BB
$L_{stop} / R_0 = 0.2$
$L_{stop} / R_0 = 0.4$
$L_{stop} / R_0 = 0.6$
$L_{stop} / R_0 = 2.2$
$L_{stop} / R_0 = 1.4$
x/R_0
y/R_0
$\phi = +30°$ $\Delta\sigma / -\sigma_{xx}^0 = 0.14$ $\tau_p / -\sigma_{xx}^0 = 0.79$
$\phi = +15°$ $\Delta\sigma / -\sigma_{xx}^0 = 0.17$ $\tau_p / -\sigma_{xx}^0 = 0.69$
$\phi = -15°$ $\Delta\sigma / -\sigma_{xx}^0 = -0.00$ $\tau_p / -\sigma_{xx}^0 = 0.54$
$\phi = -30°$ $\Delta\sigma / -\sigma_{xx}^0 = -0.16$ $\tau_p / -\sigma_{xx}^0 = 0.54$
47°
16°
-14°
$\Psi = 25°$
S_{max}



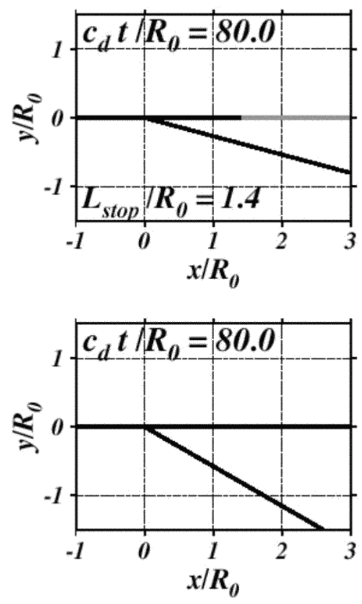
(Kame et al., *JGR*, 2003)

San Fernando 1971



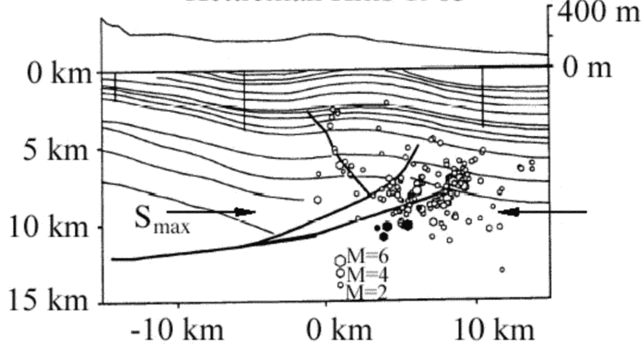
(Heaton and Helmberger, 1979)

$\Psi = 56^o,\ v_r = 0.8\ c_s$



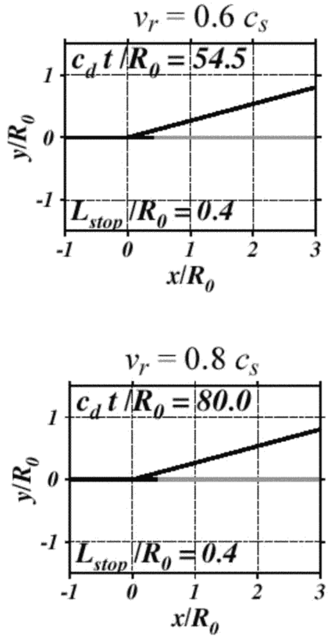
(Kame et al., *JGR*, 2003)

Kettleman Hills 1985



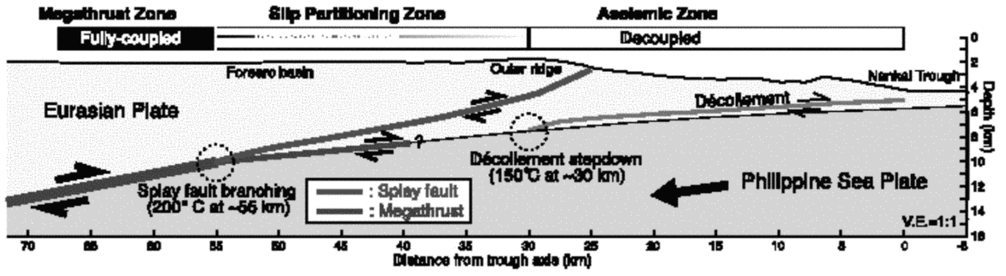
(Ekstrom et al., 1992; fault locations from Meltzer, 1989)

$\Psi = 13°$

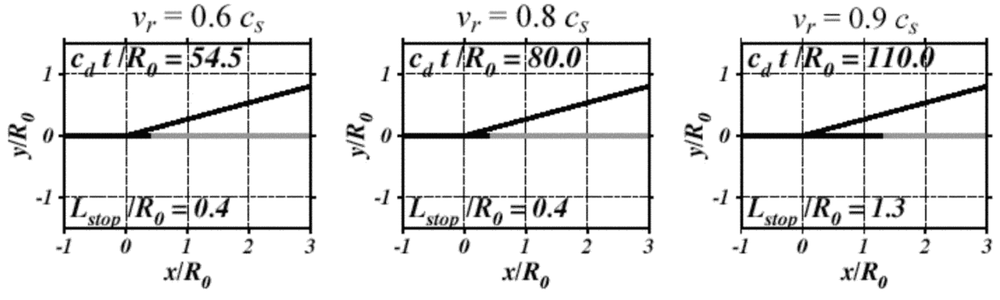


(Kame et al., *JGR*, 2003)

Nankai Trough, area of M 8.1Tonankai 1944
(Park et al., Science, 2002; Nakanishi et al., JGR, 2002)



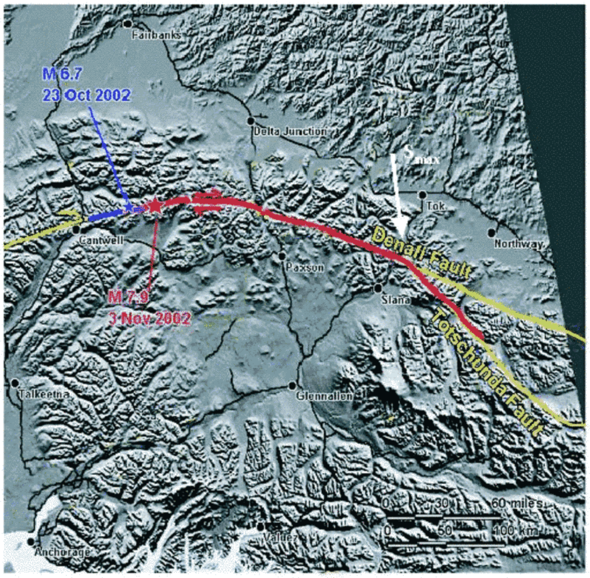
$\Psi = 13°$

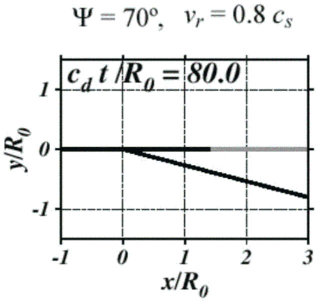


M 7.9 Denali, 3 November 2002 -- Branch from Denali Fault to Totschunda Fault

(Bhat, Dmowska, Rice and Kame, Fall 2002 AGU abstract S72F-1364)

(and *Bull. Seismol. Soc. Amer.*, 2004)





Stress direction from Ratchkovski and Hansen, 2002; Nakamura et. al., 1980; Estabrook and Davies, 1991.

Fault map from Department of Natural Resources, Division of Geological and Geophysical Surveys, Alaska

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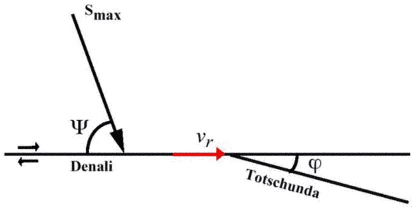
Branching parameters for Denali-Totschunda

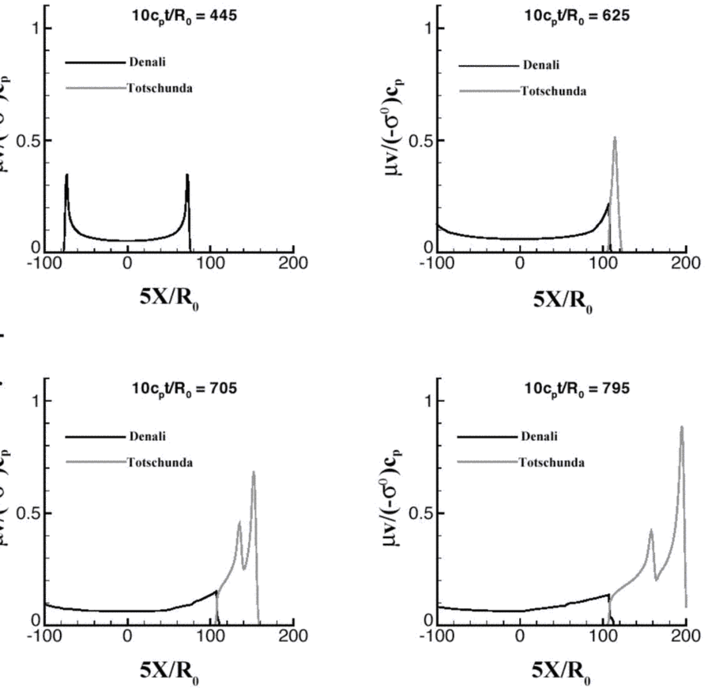
- **Orientation of the principal maximum stress with the main fault, Ψ**
  - **Ratchkovski [2003]: $\Psi \approx 80^0$**
  - **Ratchkovski and Hansen [2002]: $\Psi \approx 73^0$**
  - **Estabrook et. al. [1988] and Nakamura et. al. [1980]: $\Psi \approx 75^0$**
- **Rupture velocity near the branching region, v_r: not well constrained**
  - **Kikuchi and Yamanaka [2002]: Average $v_r = 0.8c_s$**
  - **Ellsworth et. al. [2004]: $v_r > c_s$ near PS10. $v_r = 0.8c_s$ beyond PS10**
- **Branching angle, φ**
  - **Savage and Lisowski [1991]: $\varphi \approx -15^0$ to the extensional side**

$\Psi = 70^0$, $v_r = 0.8c_s$, $\varphi = -15^0$

(Bhat et al., 2002, 2004)

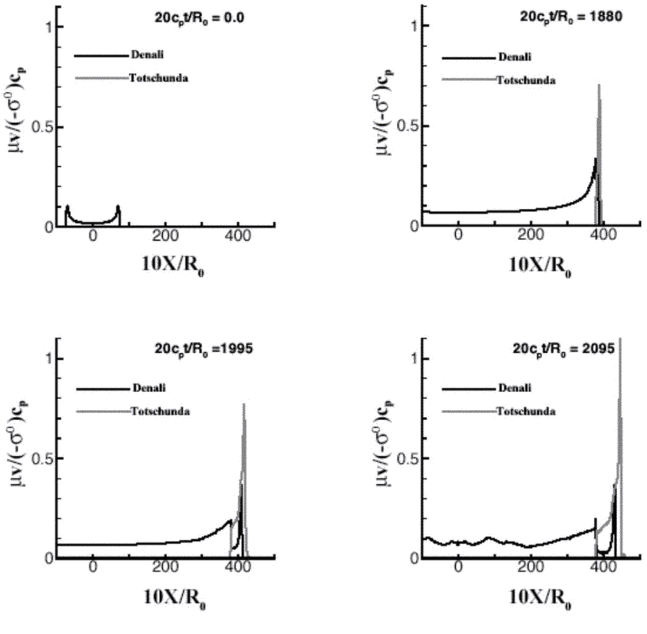
Nondimensional slip velocity **v** *vs.* distance **X** along fault traces





[For $v_r = 0.6\ c_s$: similar results]

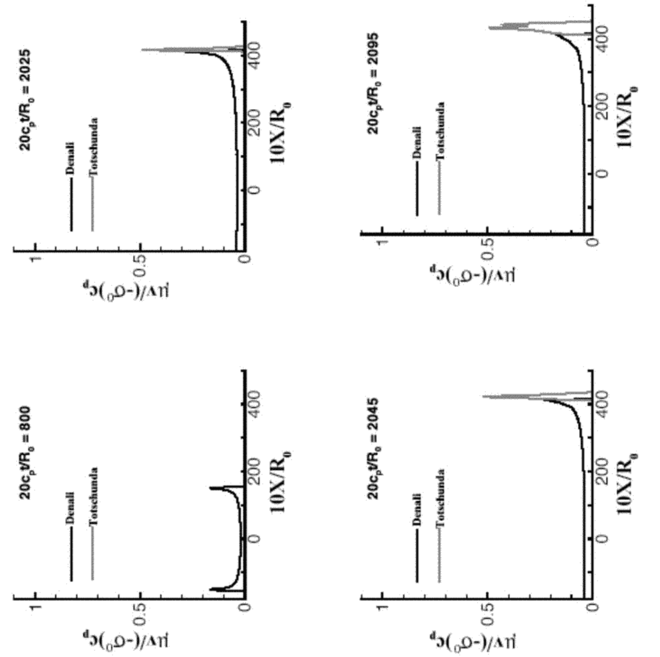
$\Psi = 70^0$, $v_r = 0.9c_s$, $\varphi = -15^0$



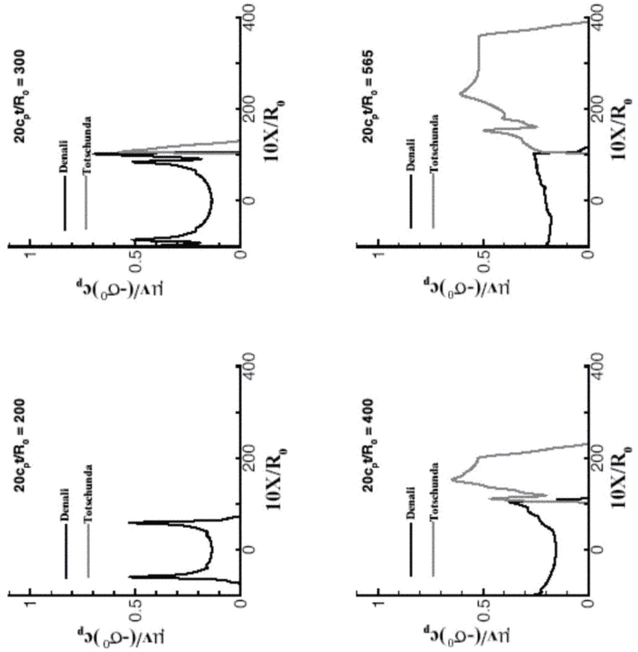
For $v_r = 0.87\ c_s$:

both faults rupture -- but *only Totschunda* ruptures if $\Psi = 80^o$ (next panel).

$\Psi = 80^0,\ v_r = 0.87c_s,\ \varphi = -15^0$



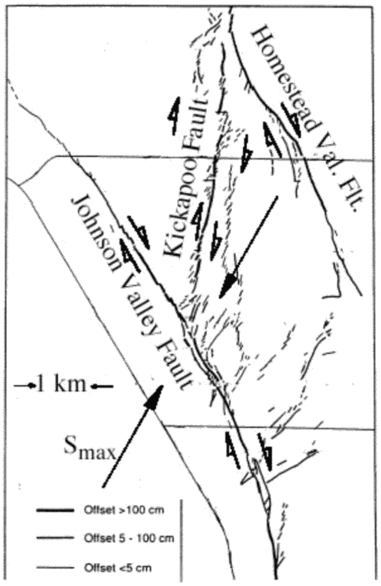
$\Psi = 70^0,\ v_r = 1.4c_s,\ \varphi = -15^0$



Intersonic
incident
rupture speed

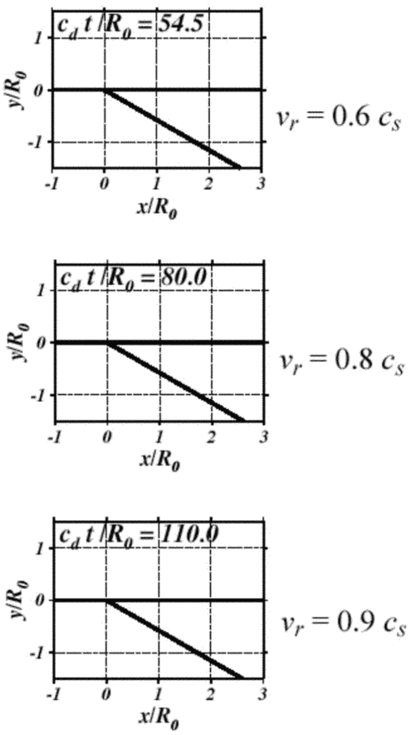
(Kame et al., *JGR*, 2003)

Landers 1992



(fault map from Sowers et al., 1994;
stress from Hardebeck and Hauksson, 2001)

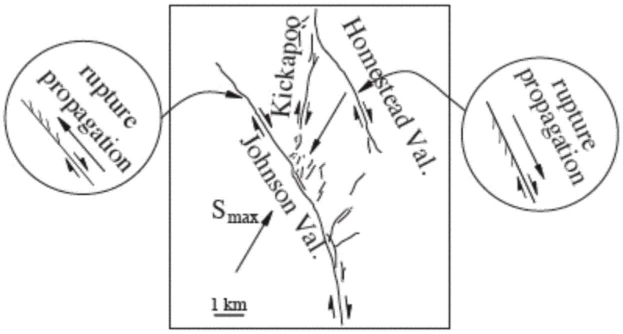
$\Psi = 56^o$



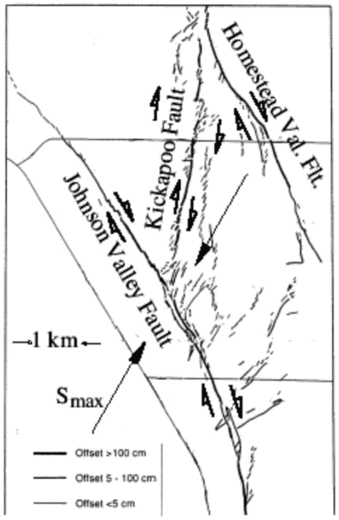
Small branching features show the direction of propagation
[Poliakov, Dmowska & Rice, *JGR,* 2002]

Map view: Steep S_{max} direction, $\Psi \approx 60^o$;
secondary failures on *extensional* side:

Landers 1992



Landers 1992



(fault map from Sowers et al., 1994;
stress from Hardebeck and Hauksson, 2001)

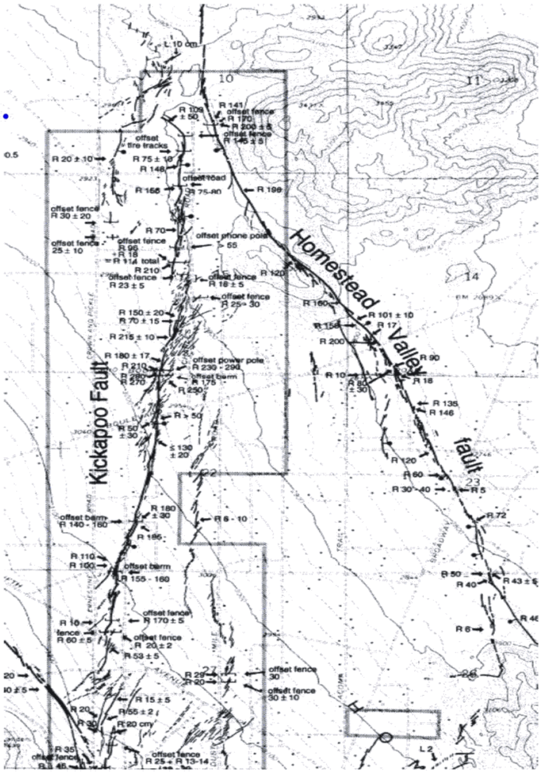
There are lots of *minor branch faults*.

How do they interact with rupture on the major fault strands?

Could they make rupture propagation very nonuniform? -- and be a source of high-frequency ground motion?

Could they arrest rupture on a major fault strand?

Examples given by Olives, Bhat, Rice & Dmowska [*EOS* 2004]



(Dmowska et al., *EOS*, 2002; Fliss et al., *JGR*. 2005)

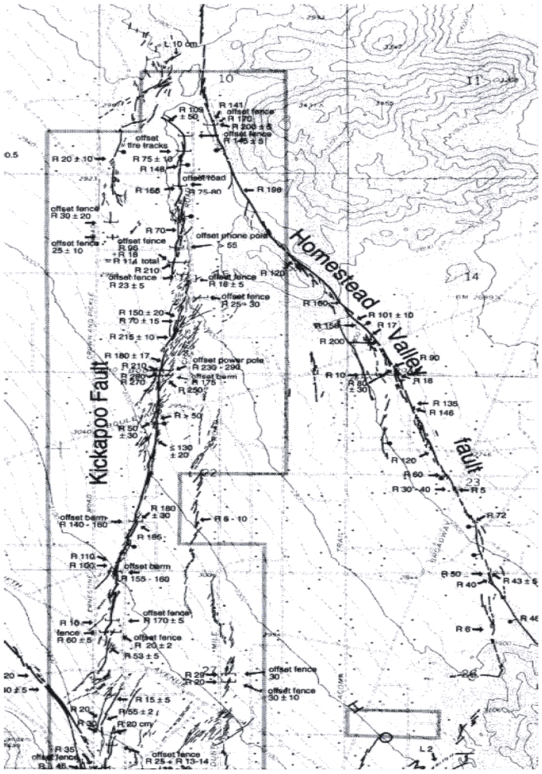
An example of *backward branching*:

Landers 1992 Earthquake

Rupture transition from Kickapoo Fault to southern part of Homestead Valley Fault (which ruptured much further to the north, off the map here):

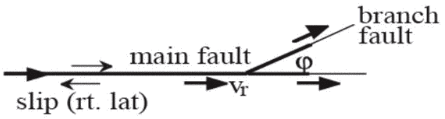
How does *backward branching* happen?

(Fault map: Sowers et al., 1994.)

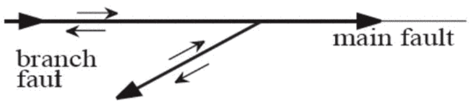


Backward Branching and Rupture Directivity

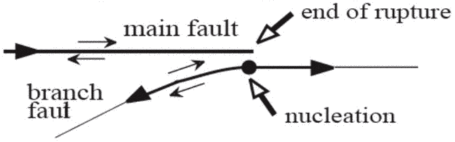
(a) Typical branching through acute angle |φ| < 90° (φ is most often negative)



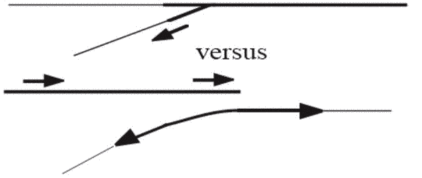
(b) Turn of rupture path through obtuse φ angle while continuing on main fault (never favored by stress field)



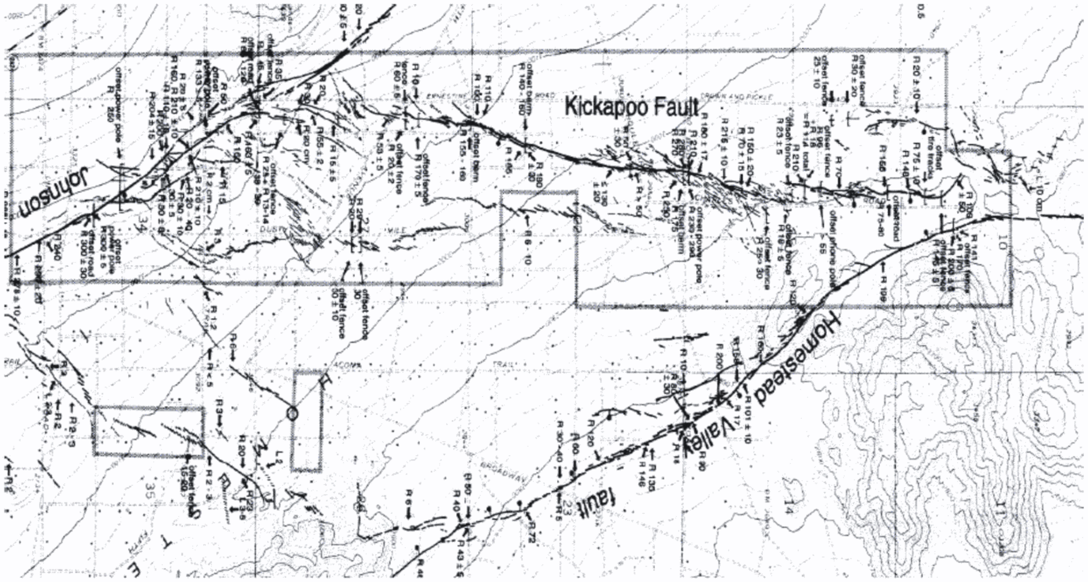
(c) Jumping mechanism; nucleation of bilateral rupture on a neighboring fault



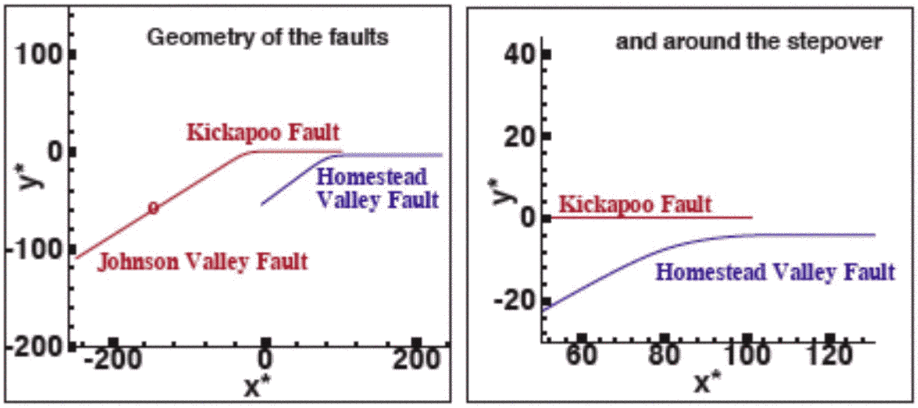
(d) Given the branch geometry, what was the direction of rupture propagation?



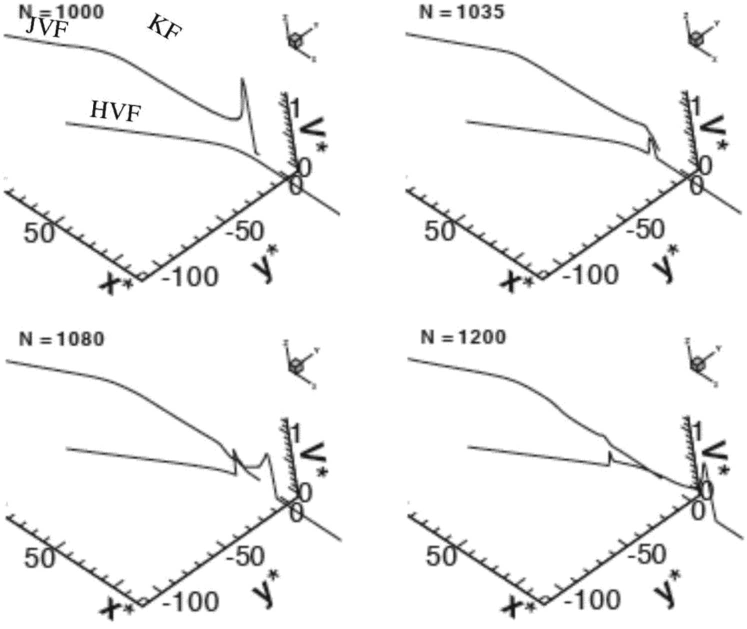
North —>



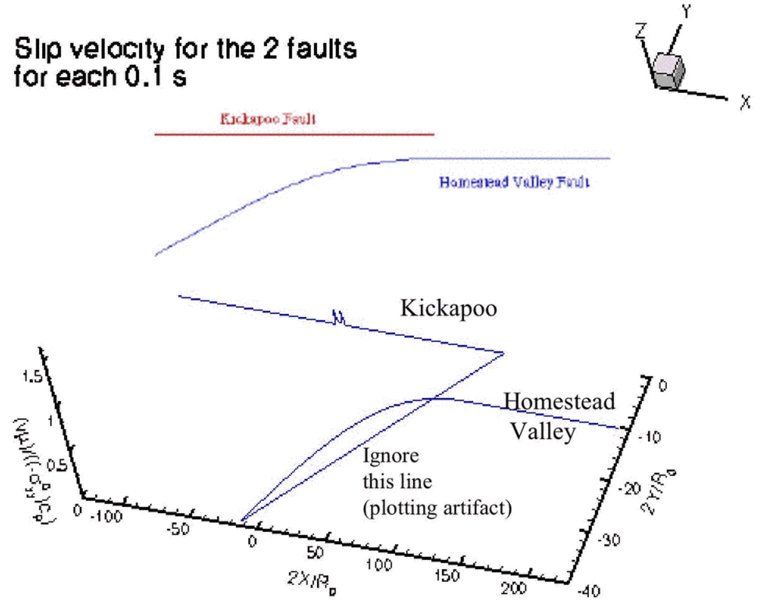
Fault geometry assumed for simulation



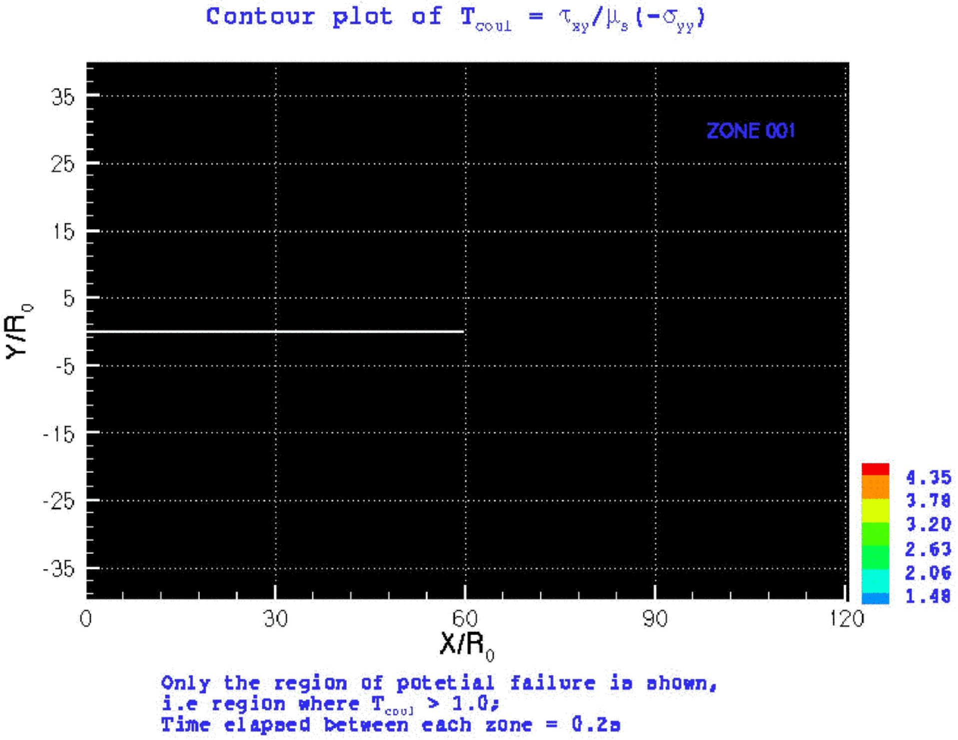
Fliss, Bhat, Dmowska & Rice [*JGR,* 2005]; simulation showing jump from the Kickapoo Fault (KF) to the Homestead Valley Fault (HVF), for a case with sub-Rayleigh v_r on the KF



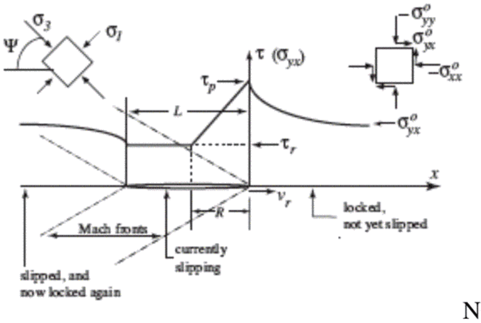
(Fliss et al. [*EOS*, 2003] version with supershear on KF; related sub-Rayleigh case [*JGR,* 2005])

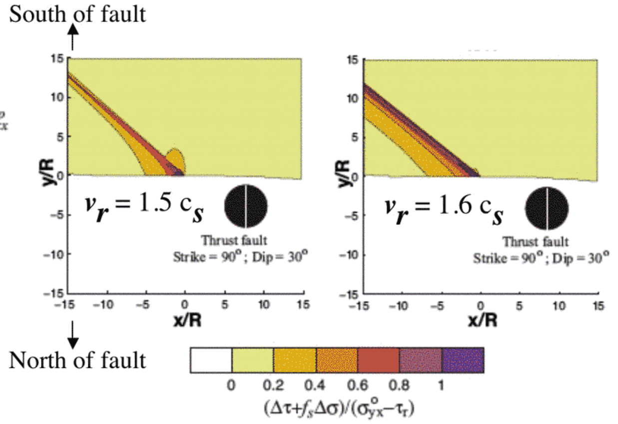


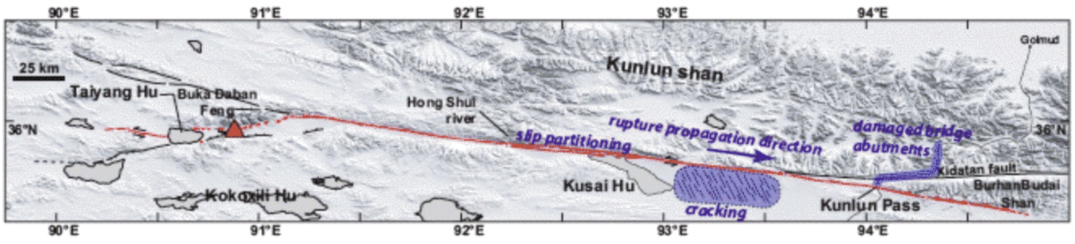
(Fliss, Bhat,et al., 2003)



Off-fault stressing associated with supershear rupture, $c_S < v_r < c_p$, and damage in 2001 M_w=8.1 Kokoxili (Kunlun), Tibet, event [Bhat, Dmowska, King, Klinger & Rice, in prep. 2005]







Summary

- Strongly driven rupture on a planar fault accelerates towards its limiting speed, c_{Limit} (= c_R for mode II, c_s for mode III).
  As v_r –> c_{Limit}, stresses *off* the main fault plane become much larger than *on* it. That nucleates failure along favorably oriented branches near the rupture front.

- Whether such failure, once nucleated, can continue to larger scales depends on the *pre-stress* state.
  For mode II rupture, S_{max} at a *shallow* angle Ψ to the fault (e.g., $\Psi < 20^o$) favors rupture to the *compressional* side; S_{max} at *steeper* angle $\Psi > 45^o$) favors *extensional* side.
  Concepts are generally supported by field observations and numerical simulations.

- Simulations also support more abundant branching at higher rupture velocities.

- Forward branching and off-fault damage in a given stress field is clearly related to rupture directivity.

- Backward branching most likely achieved as abrupt arrest on primary fault, followed by jump to a neighboring fault and bilateral propagation on it.
  Such mechanism makes diagnosing directivity of a past earthquake difficult without detailed knowledge of the branching process.

Papers and download links:

A. N. B. Poliakov, R. Dmowska and J. R. Rice, 2002: Dynamic shear rupture interactions with fault bends and off-axis secondary faulting. *Journal of Geophysical Research*, **107** (B11), *cn:* 2295, *doi:*10.1029/2001JB000572, pp. ESE 6-1 to 6-18
http://esag.harvard.edu/dmowska/PoliakovDmowskaRice_JGR02.pdf

N. Kame, J. R. Rice and R. Dmowska, 2003: Effects of pre-stress state and rupture velocity on dynamic fault branching. *Journal of Geophysical Research*, **108**(B5), *cn:* 2265, *doi:* 10.1029/2002JB002189, pp. ESE 13-1 to 13-21.
http://esag.harvard.edu/dmowska/KameRiceDmowska_JGR03.pdf

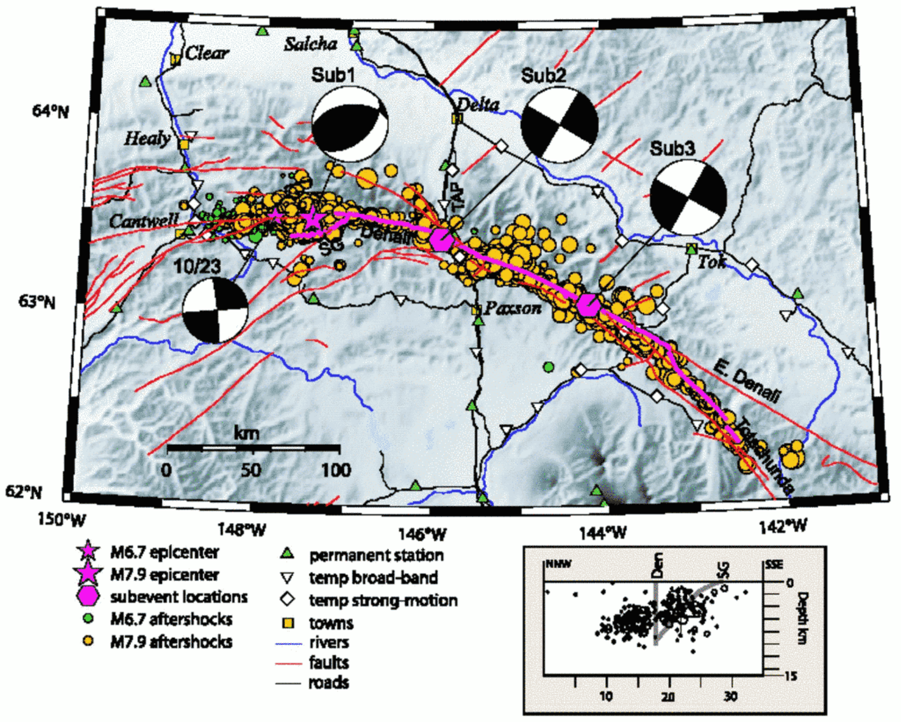
H. S. Bhat, R. Dmowska, J. R. Rice and N. Kame, 2004: Dynamic slip transfer from the Denali to Totschunda Faults, Alaska: Testing theory for fault branching. *Bulletin of the Seismological Society of America*, **94**(6B), pp. S202-S213.
http://esag.harvard.edu/dmowska/BhatDmRiKa_Denali_BSSA04.pdf

S. Fliss, H. S. Bhat, R. Dmowska and J. R. Rice, 2005: Fault branching and rupture directivity. *Journal of Geophysical Research*, 110, B06312, doi:10.1029/2004JB003368, 22 pages.
http://esag.harvard.edu/dmowska/FlissBhatDmRi_JGR05.pdf

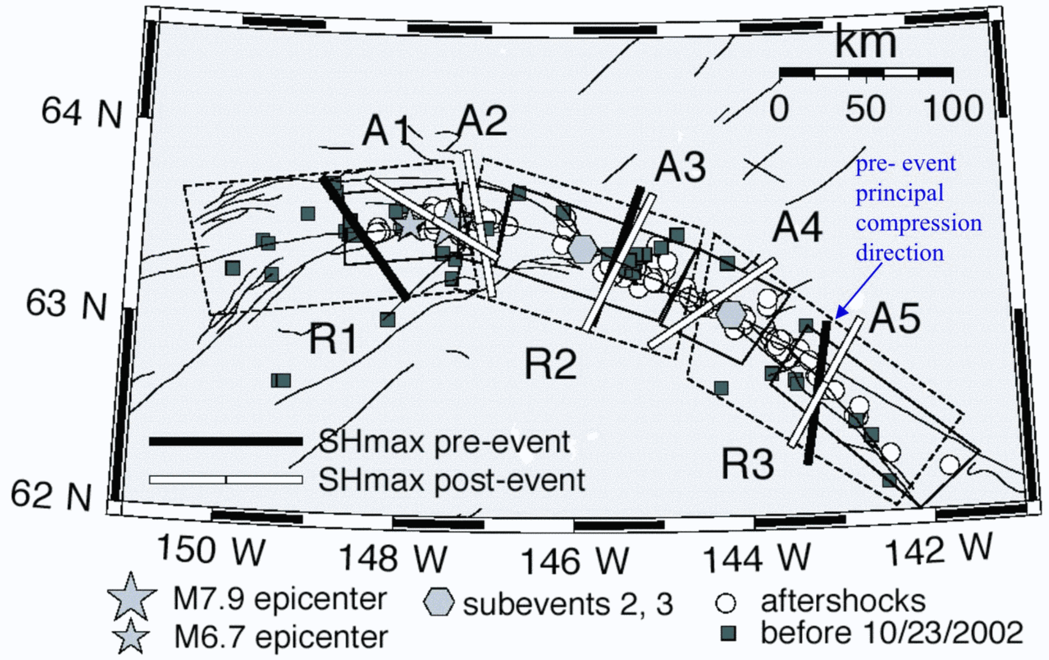
H. S. Bhat, R. Dmowska, G. C. P. King, Y. Klinger and J. R. Rice, 2005: Off-fault damage patterns due to supershear ruptures with application to the 2001 Mw 8.1 Kokoxili (Kunlun) Tibet earthquake. *semi-final draft, to be submitted to Journal of Geophysical Research*.
http://esag.harvard.edu/dmowska/BhatDmKiKlRi_supershear_drft03Aug05.pdf

Additional materials, in case needed.

$M_W = 7.9$ Denali Earthquake, 3 Nov 2002 (Eberhart-Phillips *et al., Science*, 2003)



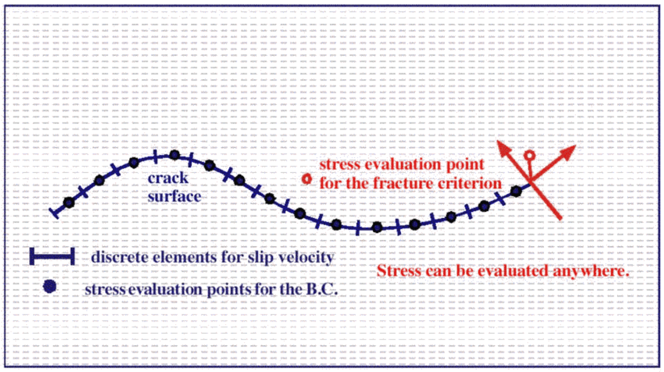
Pre-stress directions (black lines) along path of $M_W = 7.9$ Denali Earthquake, 3 Nov 2002 (Ratchkovski, *Geophys. Res. Lett.*, 2003); shows $\Psi \approx 70°$ to $80°$ near Totschunda branch



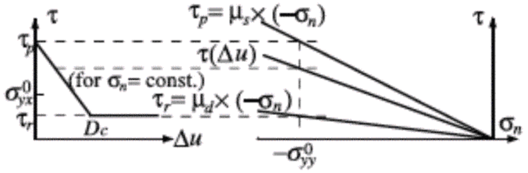
Boundary Integral Equation formulation, based on Kame and Yamashita (*GJI*, 1999), with Coulomb slip-weakening

$$u_k(x,t)=\int_{-\infty}^{t}\int_{Fault} C_{pqrs}\underbrace{\boxed{\Delta\dot{u}_r(x',t')}}_{\text{slip velocity}}n_s(x')\overbrace{\frac{\partial G_{kp}(x-x',t-t')}{\partial x'_q}}^{\text{Heaviside Green's function}}ds'dt'$$

$$\overset{\text{stress}}{\boxed{\sigma_{ij}(x,t)}}=C_{ijkl}\partial u_k(x,t)/\partial x_l$$

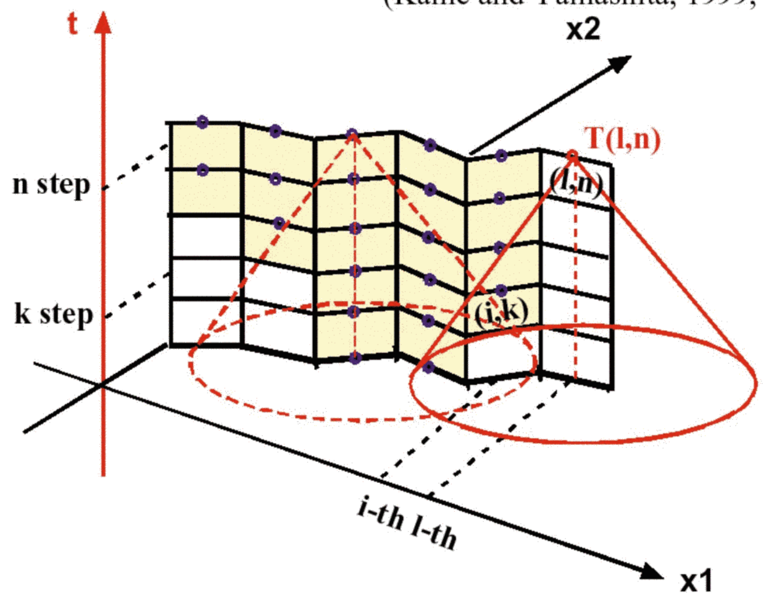


Slip-weakening model of frictional failure:
τ = shear stress,
σ_n = normal stress,
Δu = fault slip.



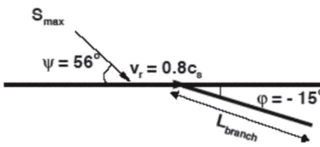
Boundary Integral Equation Method

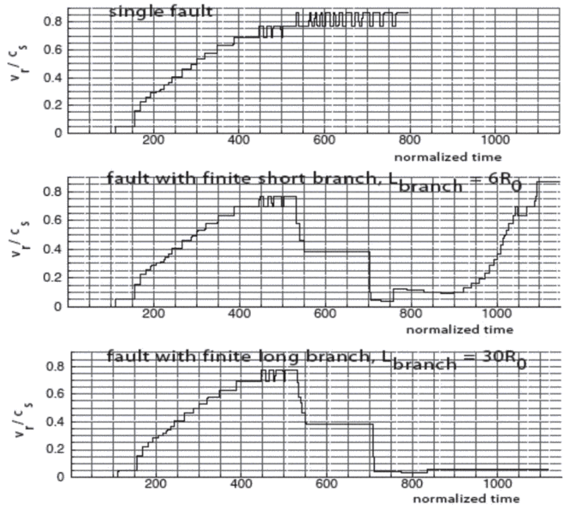
(Kame and Yamashita, 1999, *GJI*)

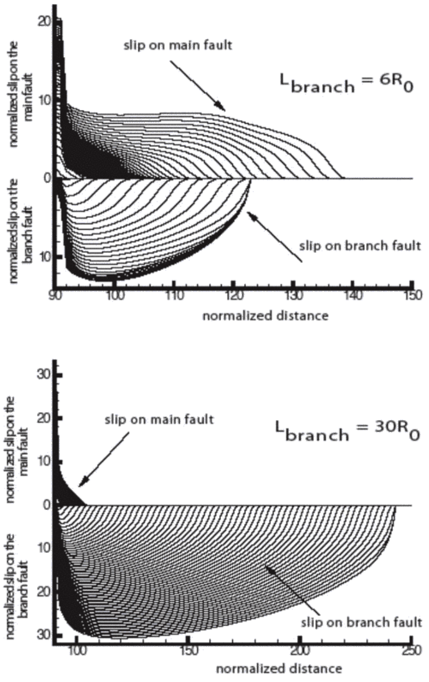


Effect of a branch fault of *finite length*, in a case for which an infinite branch would **capture the rupture *exclusively*** (no continuation on main fault)

(Olives, Bhat, Rice & Dmowska, 2004)



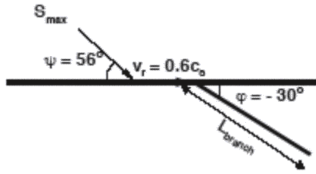


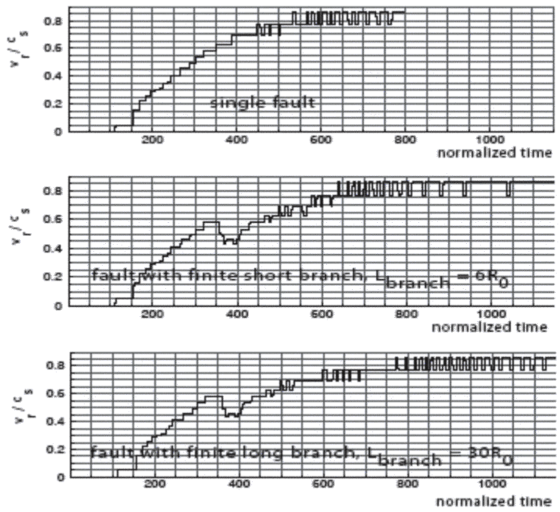


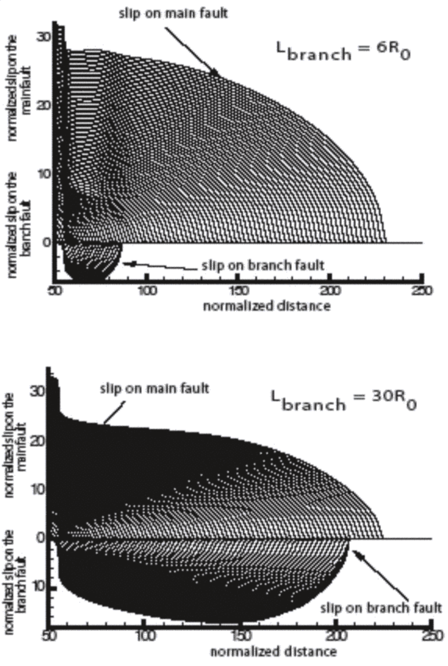
Influence of finite branched system on rupture velocities on the main fault. For the model parameters described on the top most figure, a short branch has the effect of slowing down and speeding up the rupture on the main fault whereas a long branch slows down the rupture for much longer duration. This should introduce small scale (spatial and temporal) complexities in the slip distribution (right panel) and also could be a source of high-frequency ground motions [Olives et al. 2004].

Effect of a branch fault of ***finite length***, in a case for which rupture would ***both*** **continue on the main fault** ***and*** **take the branch**.

(Olives, Bhat, Rice & Dmowska, 2004)







Influence of finite branched system on rupture velocities on the main fault. For the model parameters described on the top most figure, a short branch has the effect of slowing down and speeding up the rupture on the main fault whereas a long branch slows down the rupture for a much longer duration. This should introduce small scale (spatial and temporal) complexities in the slip distribution (right panel) and also could be a source of high-frequency ground motions [Olives et al. 2004].