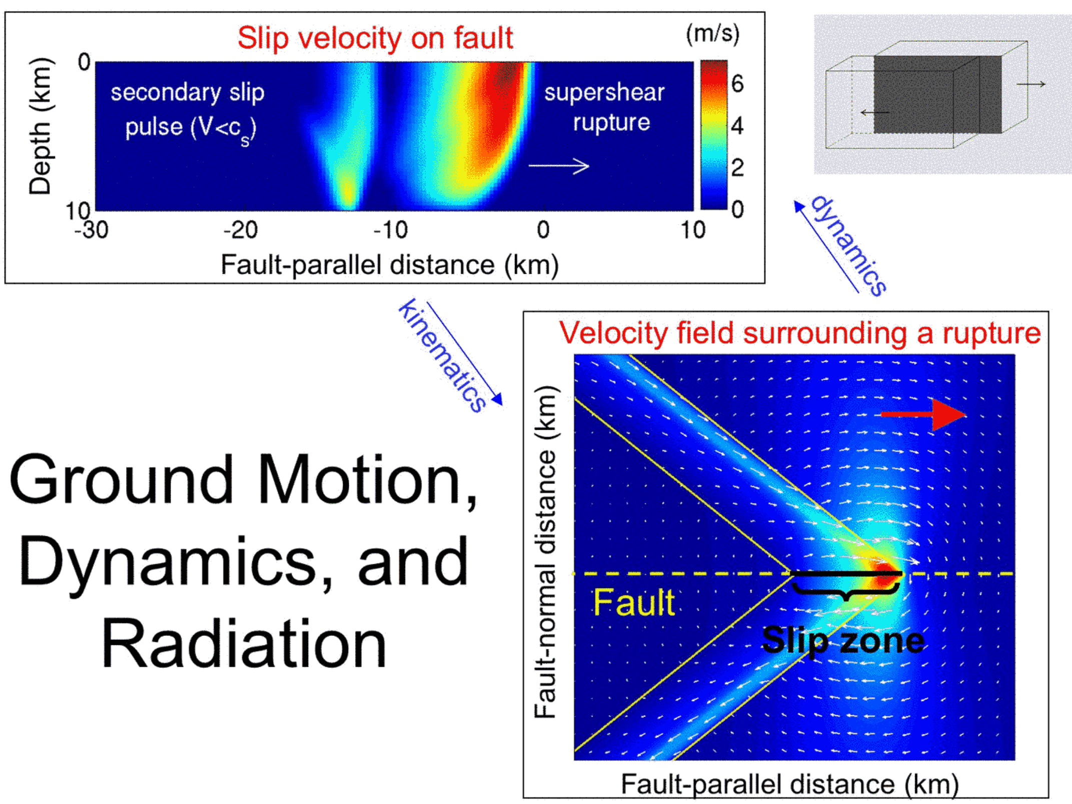
The Dynamics and Near-Source Ground Motion of Supershear Earthquakes

Eric Dunham
Harvard University (formerly UCSB)

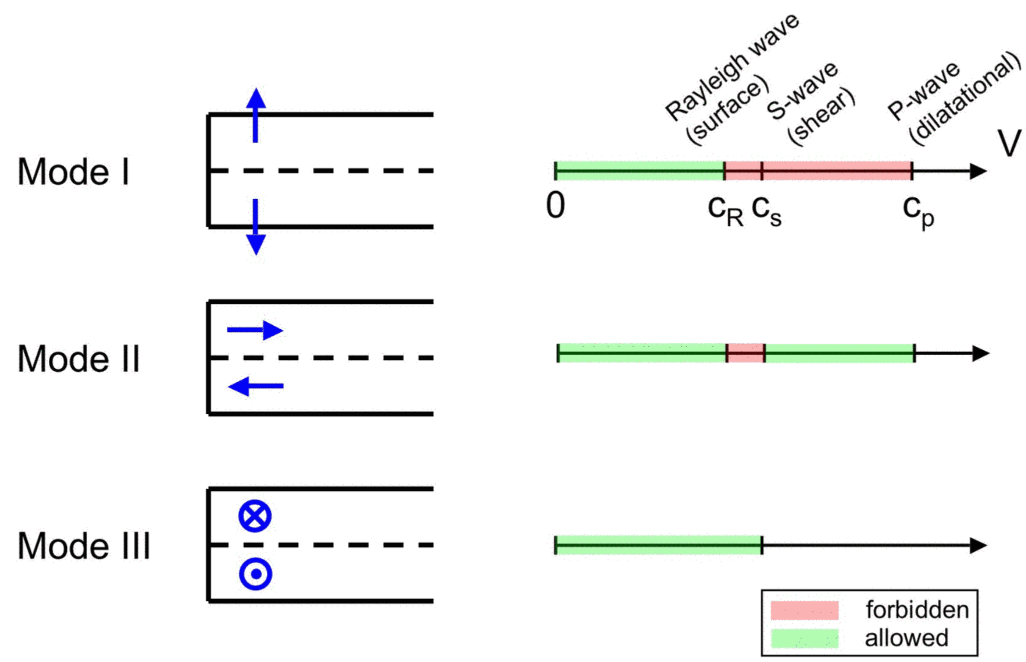
Ralph Archuleta, Jean Carlson,
Morgan Page, Pascal Favreau

[Thanks also to Lars Bildsten and Jim Langer]

Ground Motion, Dynamics, and Radiation

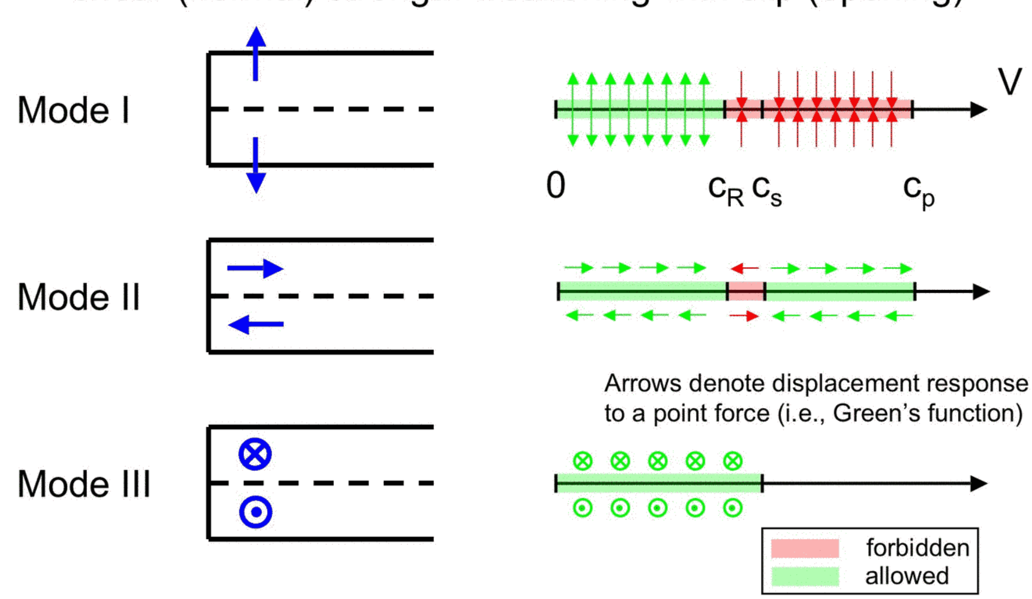


Limiting Rupture Velocities



Limiting Rupture Velocities

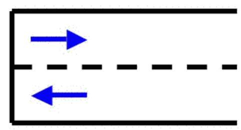
Transient elastodynamic response must be consistent with shear (normal) strength weakening with slip (opening)

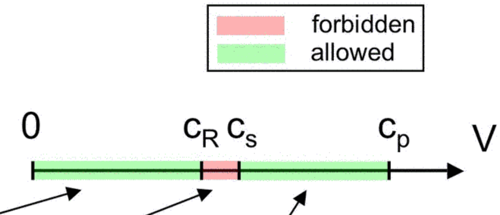


History / Terminology

Mode II

typical for strike-slip faults (looking down on fault)





sub-Rayleigh
- "typical" of earthquakes
- predicted limiting velocity from early theoretical studies

forbidden

intersonic / supershear
- established theoretically in 1970s [e.g., Burridge, 1973; Andrews, 1976]
- seismically observed [e.g., Archuleta, 1984; …]
- experimentally observed [Rosakis et al., 1999]

Character of radiated ground motion is different between the two velocity regimes

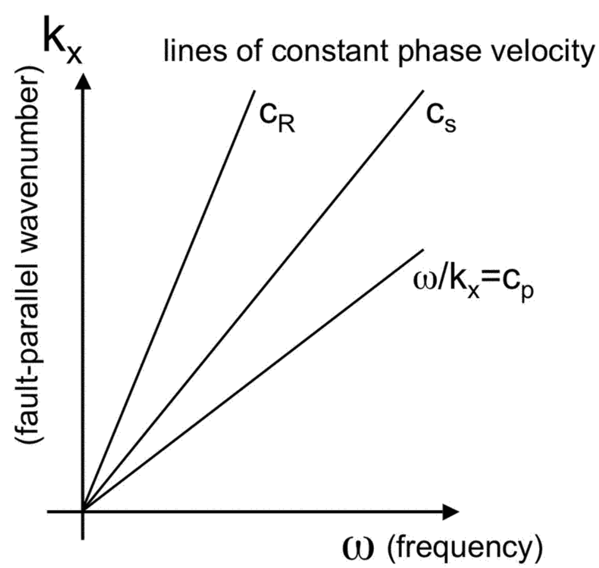
Fourier domain (frequency-wavenumber)

(e.g., particle velocity)

$$v_i(x,y,t)$$
$$\downarrow$$
$$\hat{v}_i(k_x,\omega)e^{i(k_x x+k_y y-\omega t)}$$

$$|\omega/k_x| < c \;\; \text{evanescent}$$
$$|\omega/k_x| > c \;\; \text{radiating}$$

far-field signals only from radiating waves



Excitation by Source Process

(e.g., slip velocity)

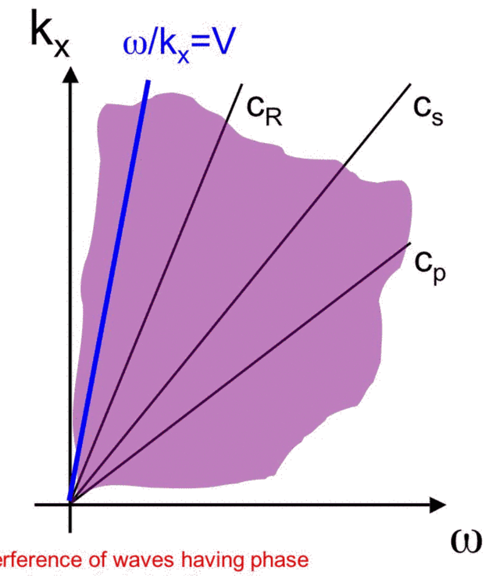
$$\Delta v_x(x,t) = \boxed{\Delta v(x - Vt)} + \boxed{\delta v(x,t)}$$

steady-state: $\Delta v(x - Vt)$

deviations: $\delta v(x,t)$

$$\downarrow$$

$$\Delta\hat{v}_x e^{ik_x(x - \frac{\omega}{k_x}t)}$$

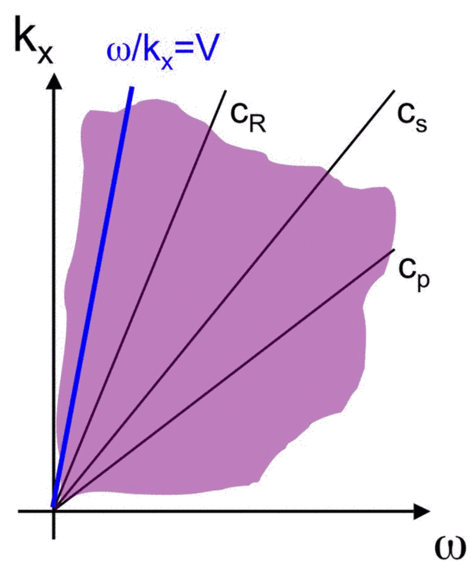


A coherent source process causes constructive interference of waves having phase velocity V, while waves having other phase velocities destructively interfere.

Excitation by Source Process

Steady-state represents coherent (probably low-frequency) portion of source process

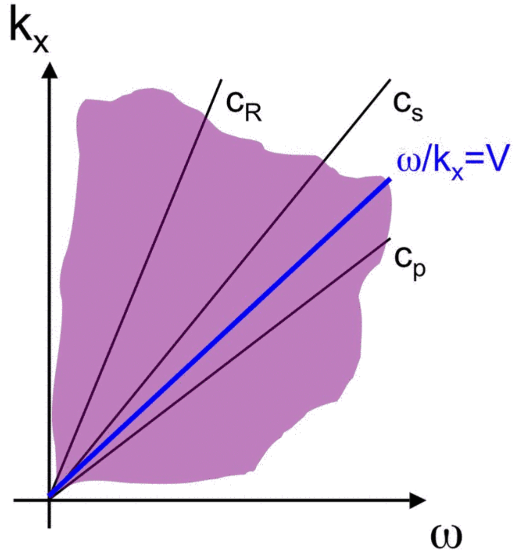
sub-Rayeigh ruptures coherently feed:
- evanescent P-waves
- evanescent S-waves



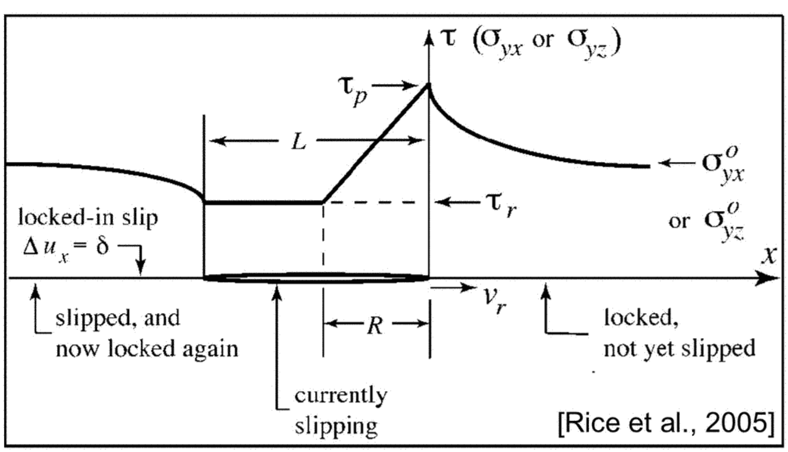
Excitation by Source Process

Steady-state represents coherent (probably low-frequency) portion of source process

intersonic ruptures coherently feed:
- evanescent P-waves
- radiating S-waves

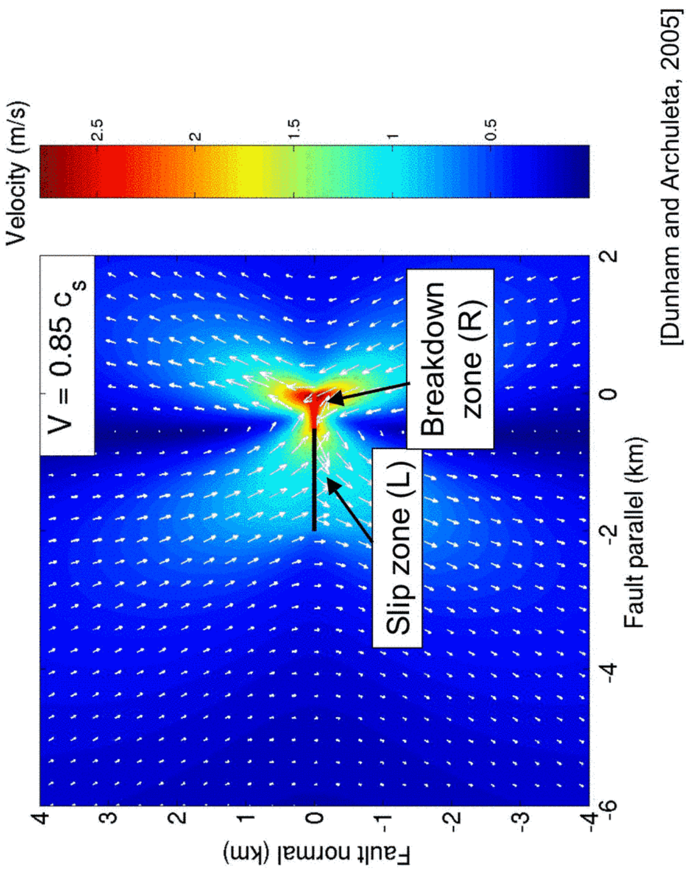


Steady-State Solutions: Slip-Pulse Model

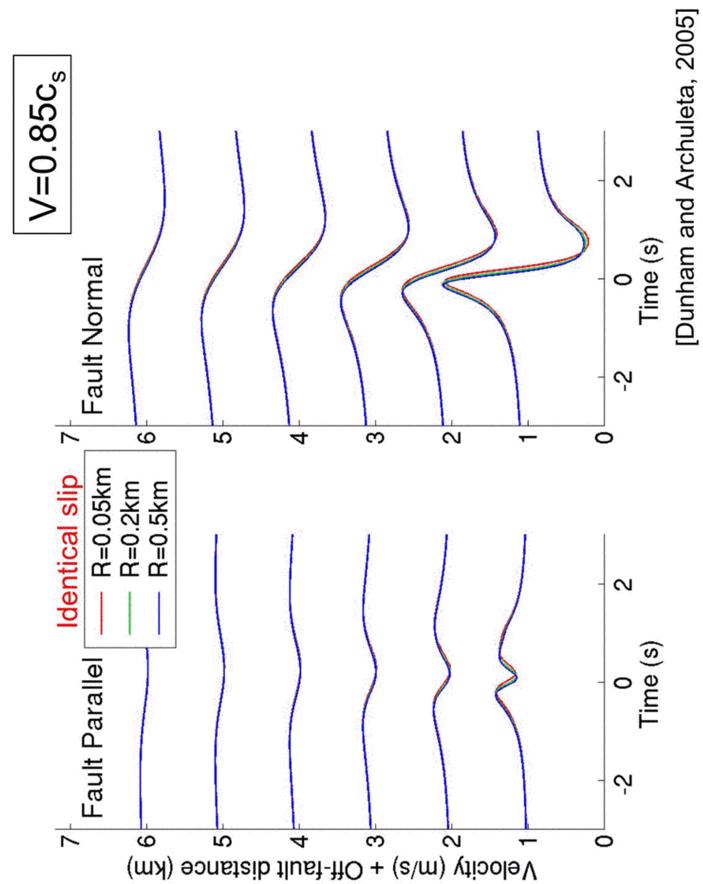


Extension to intersonic regime to study near-source ground motion (particle velocity field) by Dunham and Archuleta [2005]

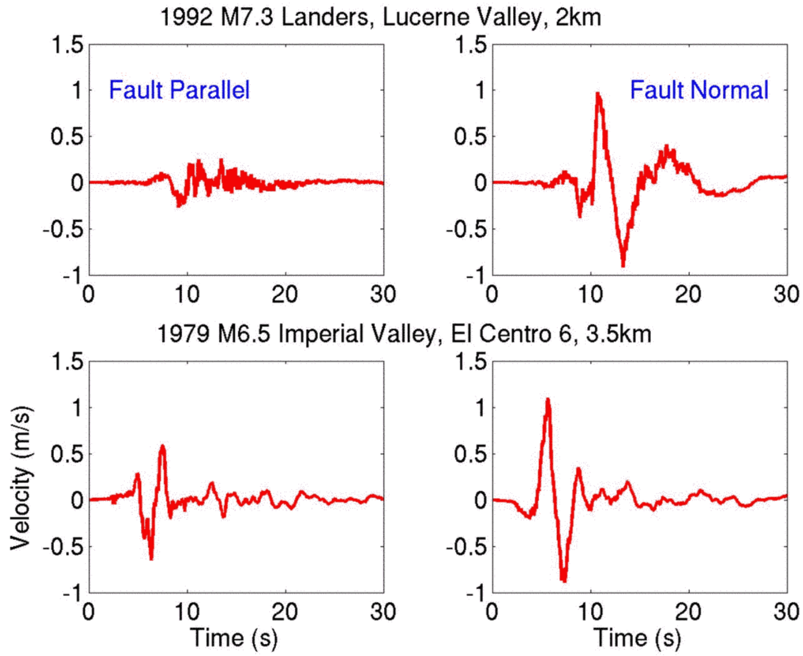
Velocity Field for Sub-Rayleigh Rupture



Synthetic Seismograms: Sub-Rayleigh



Typical Near-Source Seismograms



What properties of the rupture process are measurable?

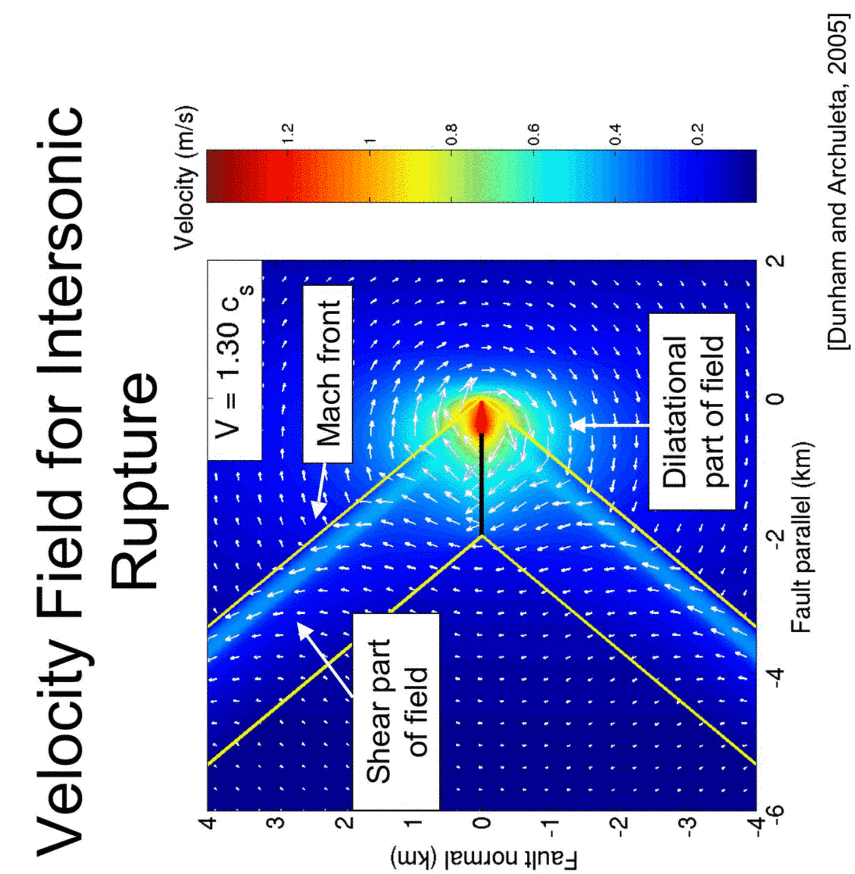
More than a few km from the fault, ground motion is only sensitive to:

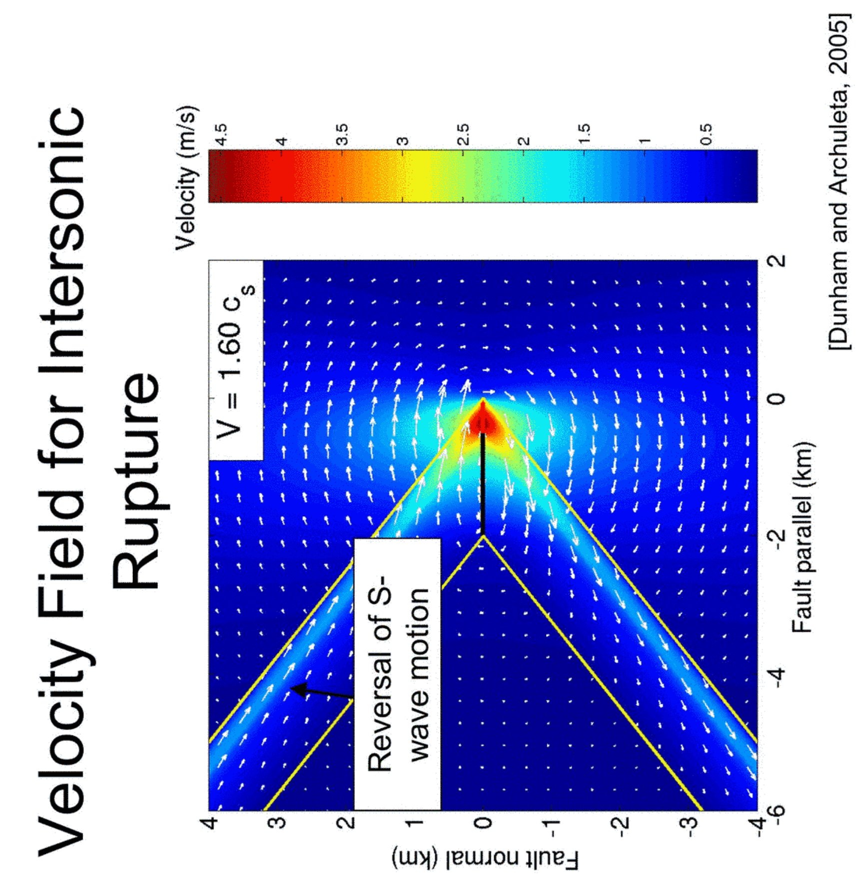
Kinematic parameters:
1. rupture speed V
2. slip zone length L (or rise time)
3. final slip

Not sensitive to:

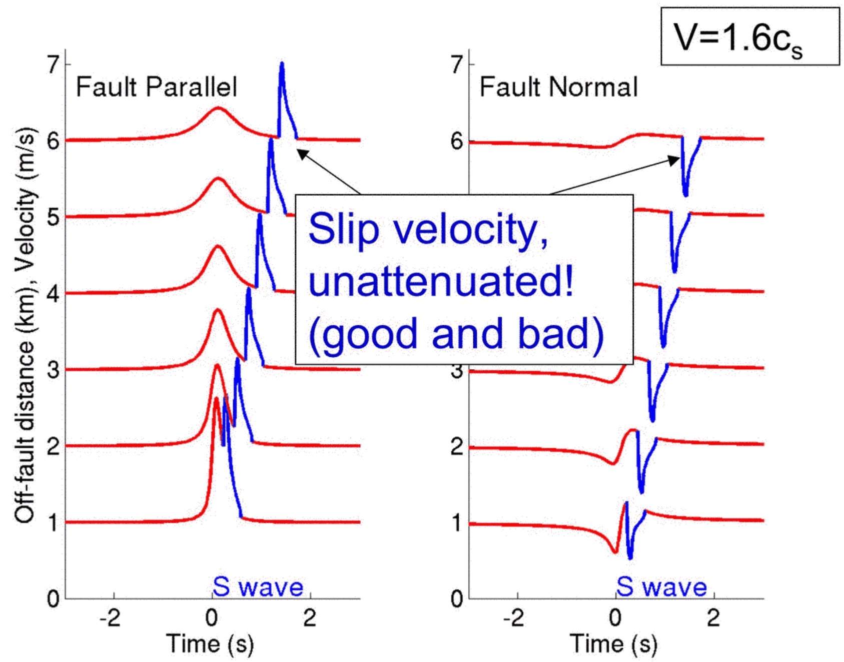
1. breakdown zone length R

This explains why *kinematic* models have been so successful and is bad news for seismologists interested in *dynamics*…


Velocity Field for Intersonic Rupture
V = 1.30 c_s
Mach front
Dilatational part of field
Shear part of field
Velocity (m/s)
Fault parallel (km)
Fault normal (km)
[Dunham and Archuleta, 2005]


Velocity Field for Intersonic Rupture
V = 1.60 c_s
Reversal of S-wave motion
Velocity (m/s)
Fault parallel (km)
Fault normal (km)
[Dunham and Archuleta, 2005]

Synthetic Seismograms: Intersonic



[Dunham and Archuleta, 2005]

Conditions for Supershear

What selects a supershear solution instead of a sub-Rayleigh solution?

- General rule: supershear ruptures occur on sections of the fault close to failure (quantified in 2D by Andrews [1976])
- Coexistence of solutions having same fracture energy, but different stress drops and production of radiated seismic energy
- Key is transient evolution of rupture!

Supershear Transition Dynamics

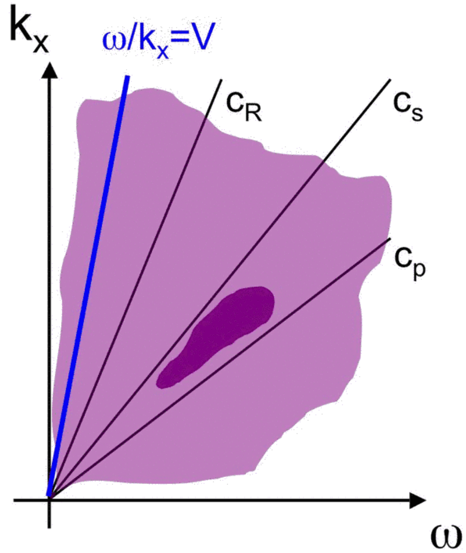
$$\Delta v_x(x,t) = \boxed{\Delta v(x - Vt)} + \boxed{\delta v(x,t)}$$

steady-state: $\Delta v(x - Vt)$

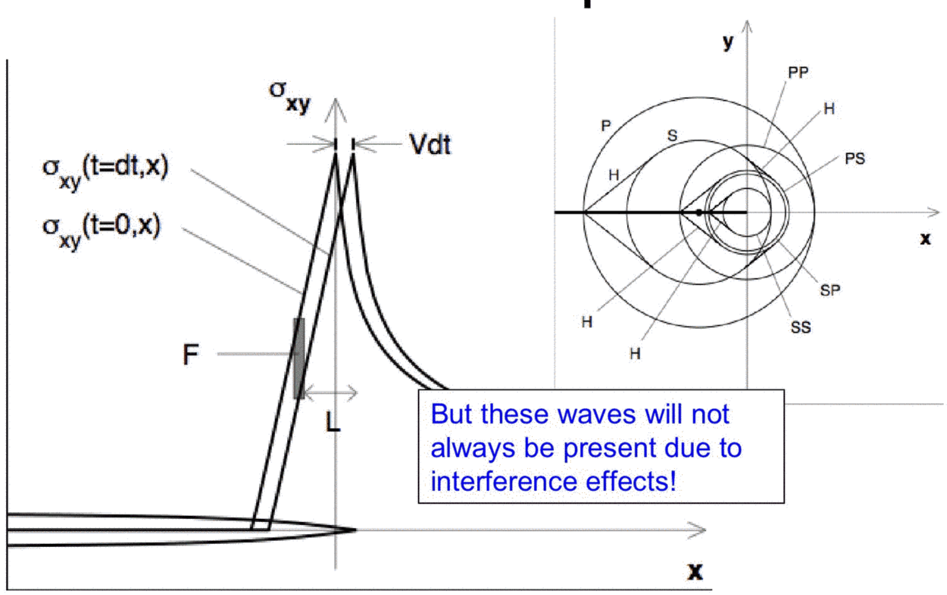
deviations: $\delta v(x,t)$

Generates stresses ahead of rupture that satisfy nucleation criterion:

- intersonic phase velocities
- sufficient amplitude
- phase correlated at sufficiently long wavelengths



Stress Transmission during Advance of the Rupture Front



[Dunham and Archuleta, 2004]

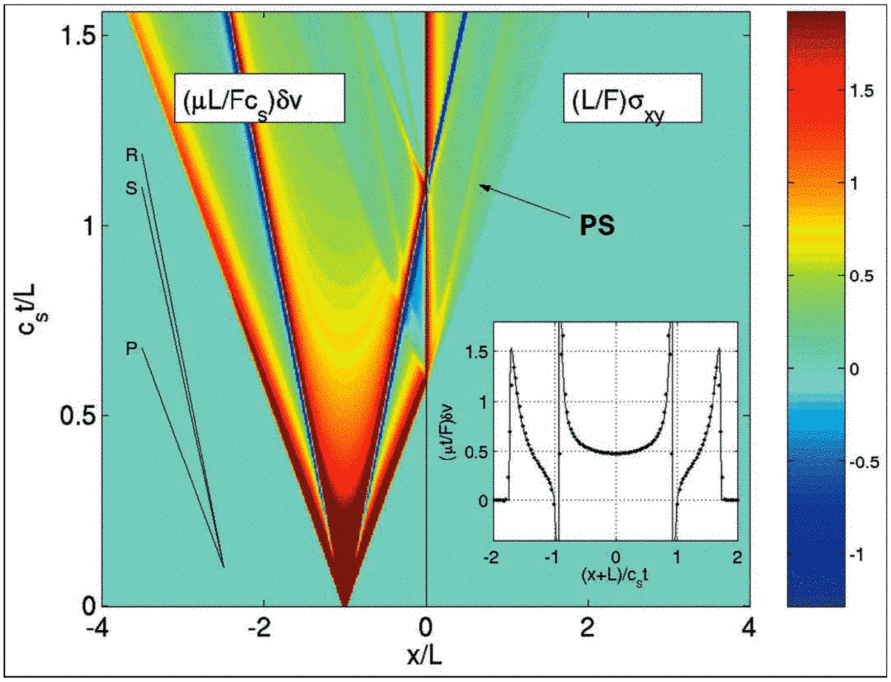
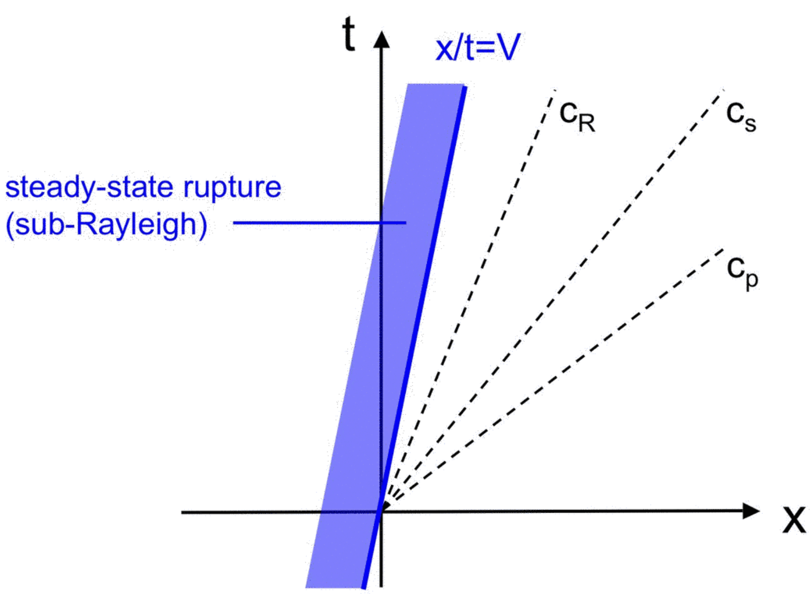


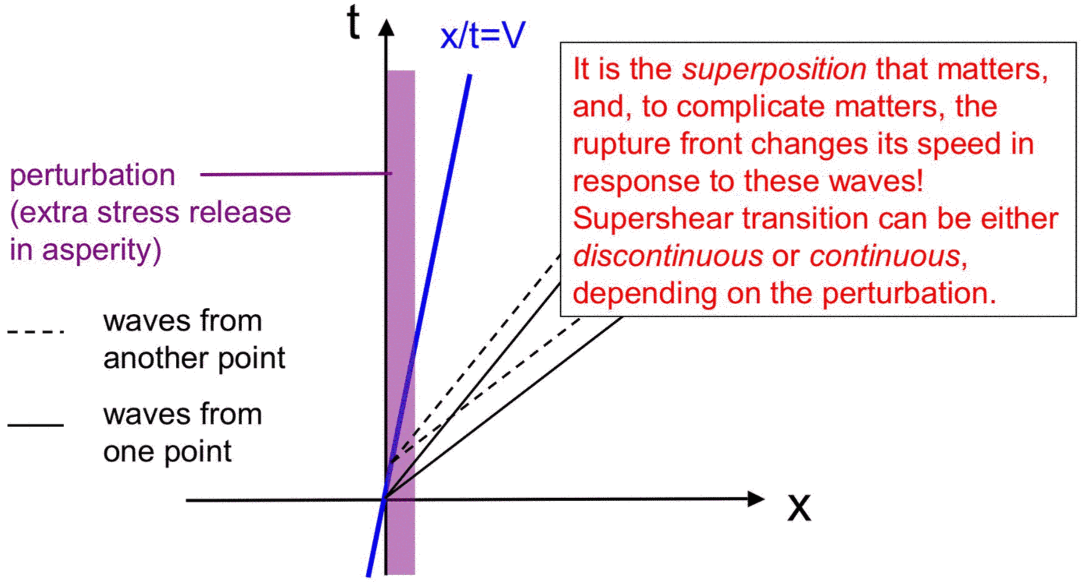
Figure 5. Evolution of slip velocity (x<0) and shear traction (x>0) after the step-function application of a line stress drop of magnitude F at x=-L behind a stationary crack tip.

[Dunham and Archuleta, 2004]

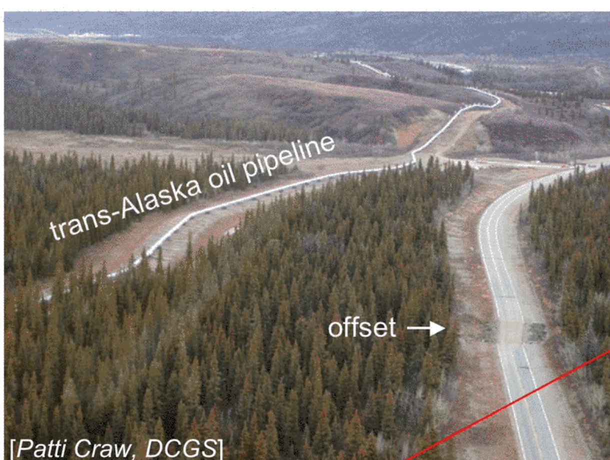
Supershear Transition Dynamics



Supershear Transition Dynamics

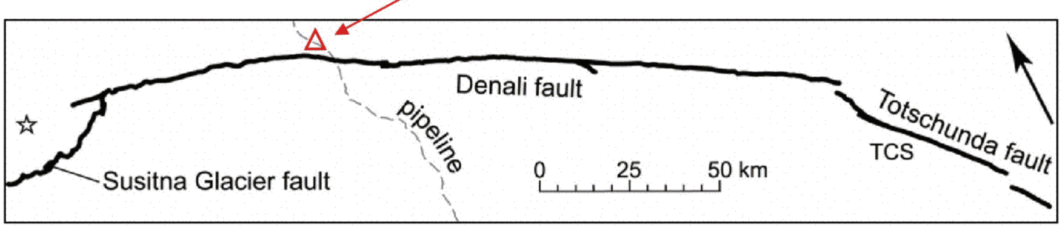


2002 Denali Fault Earthquake

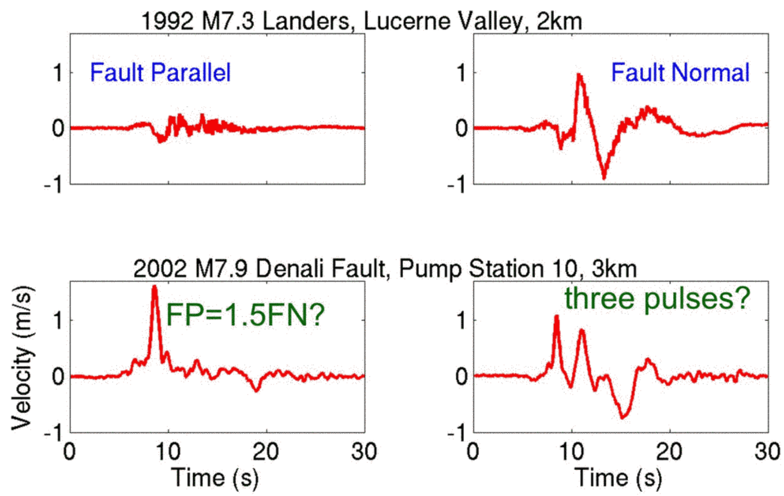


Pump Station 10
(PS10)

3km N of fault



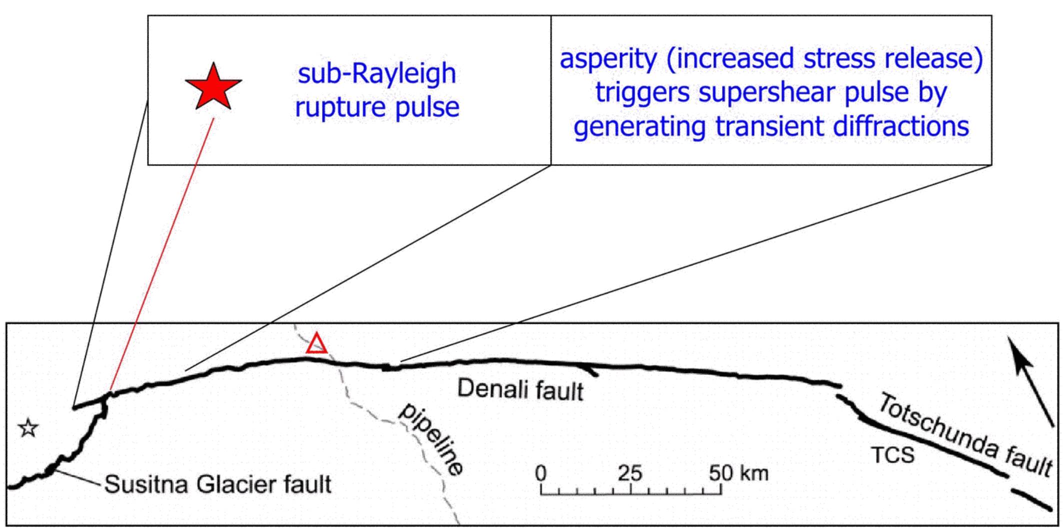
A Puzzle in the Seismograms

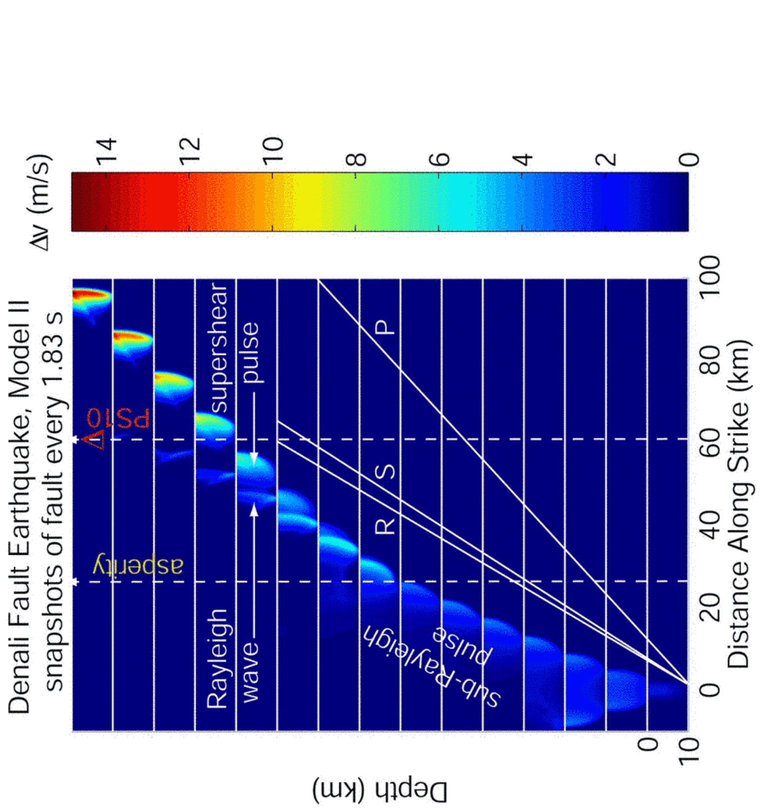


PS10 data processing and supershear kinematic model by Ellsworth et al. [2004]

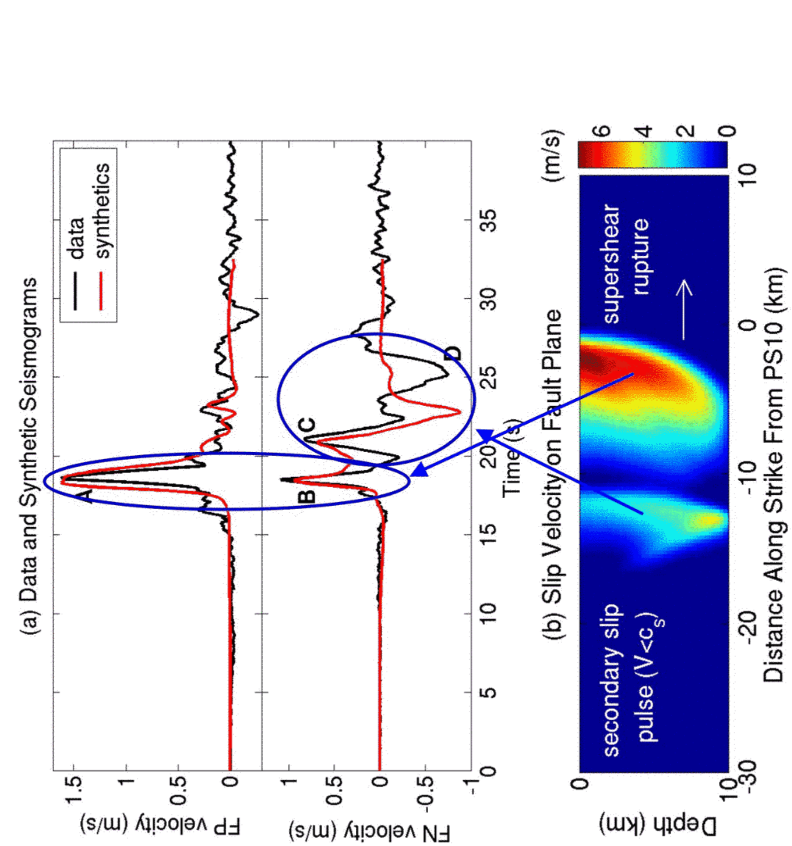
A Spontaneous Dynamic Rupture Model

(fault slips according to slip-weakening friction law, with objective of identifying qualitative features of seismograms)



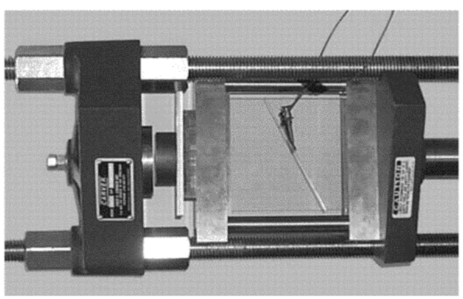


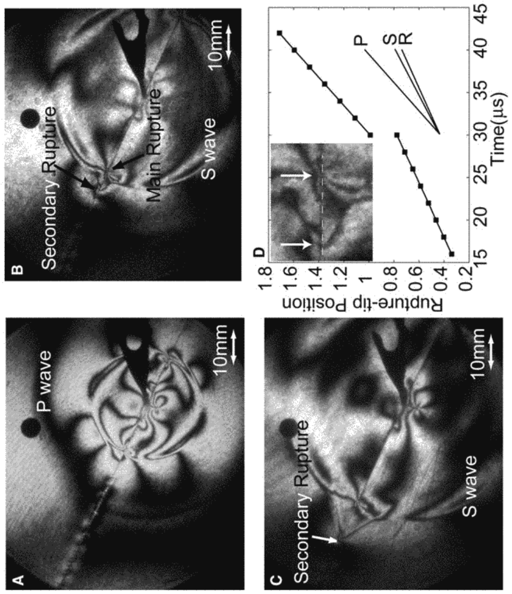
[Dunham and Archuleta, 2004]



[Dunham and Archuleta, 2005]

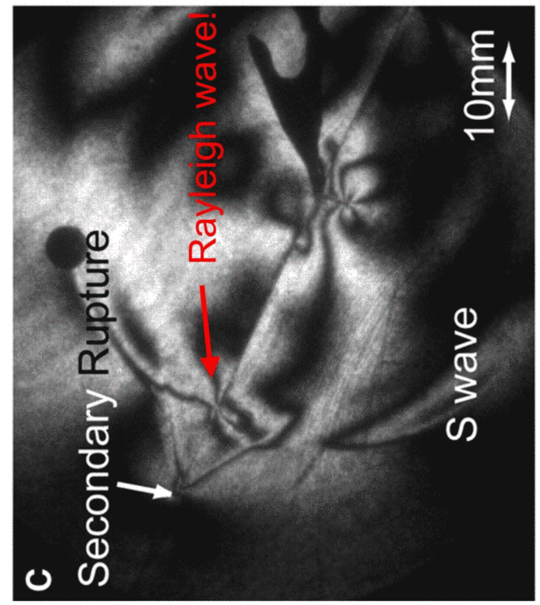
Laboratory Confirmation



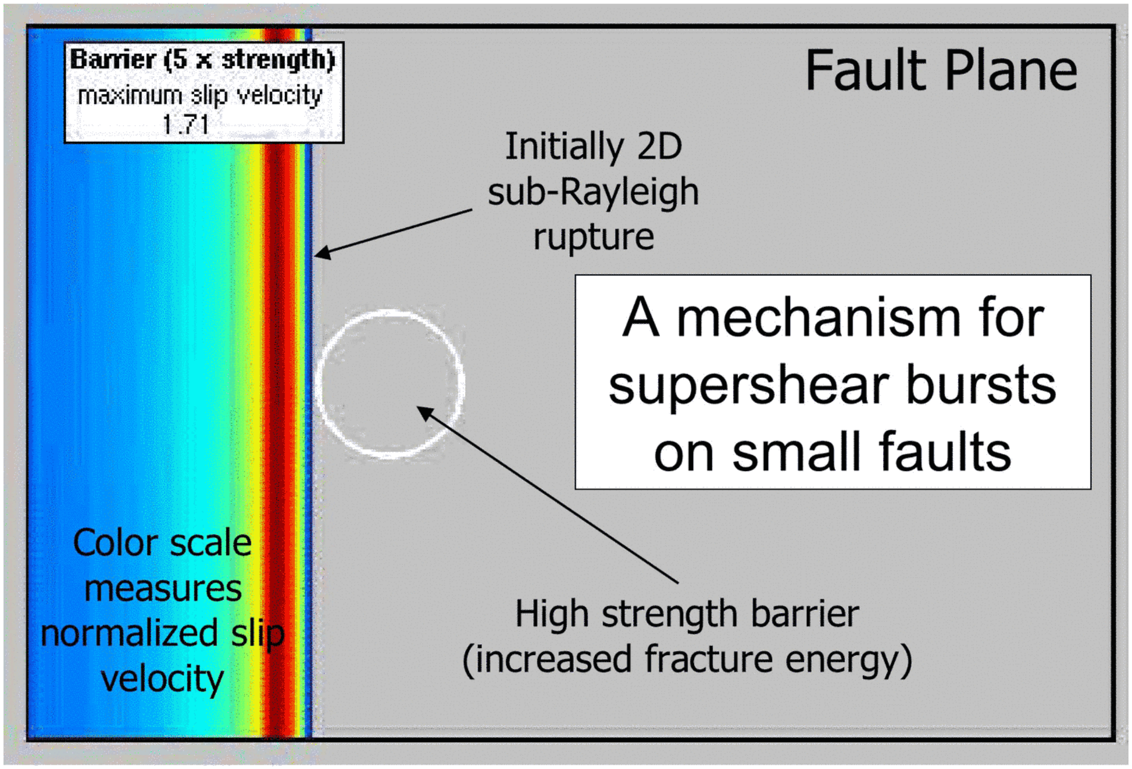


[Xia et al., 2004]

Laboratory Confirmation

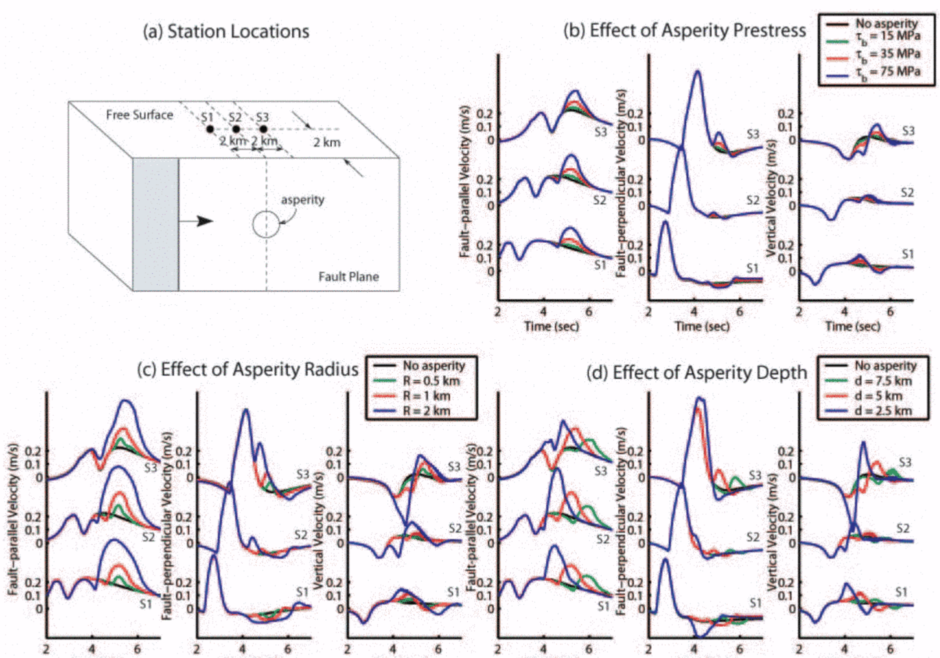


[Xia et al., 2004]



[Dunham et al., 2003]

Synthetic Seismograms



[Page et al., in press]

Concluding Thoughts

How often will supershear earthquakes occur?

Is there a minimum magnitude?

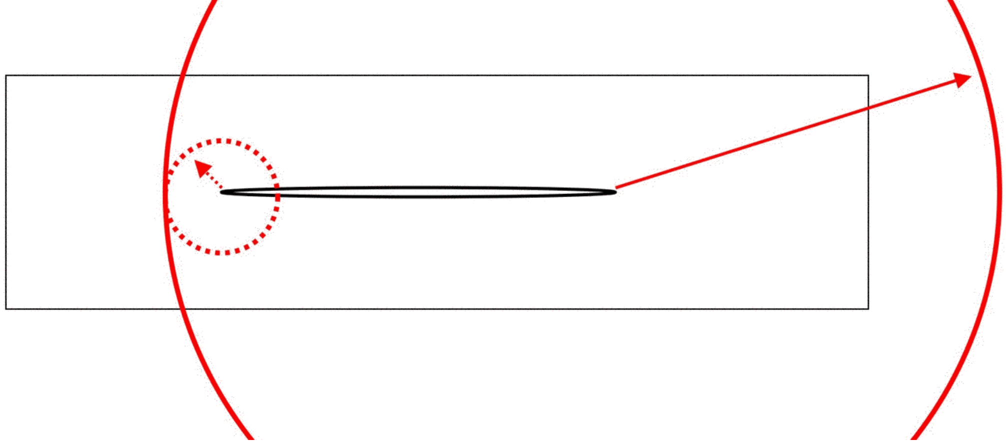
The supershear transition occurs whenever the stress field ahead of a sub-Rayleigh rupture meets some nucleation criterion. This requires heterogeneities on the fault to be sufficiently large (both in amplitude and spatial extent), and suggests that the duration of supershear propagation will be related to the size of the triggering heterogeneity.

Open Issues with Denali

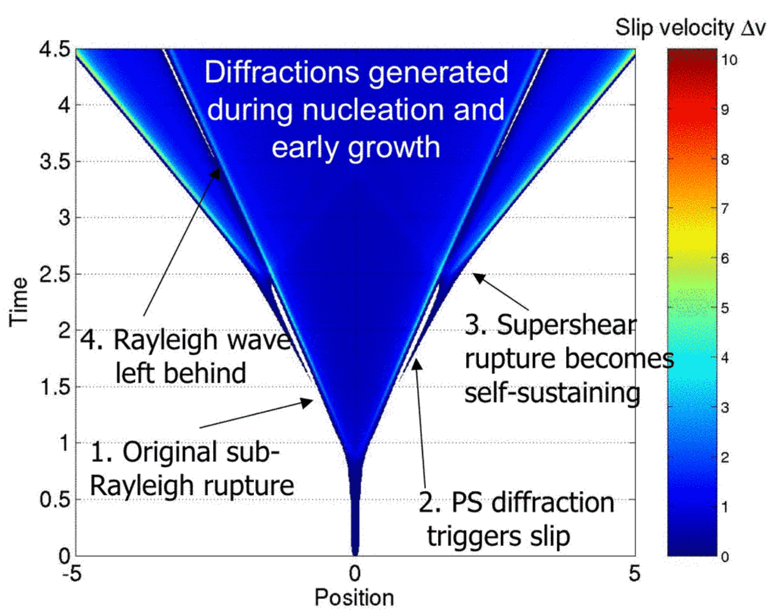
- Relative amplitude of supershear to Rayleigh-wave amplitude requires critical stress level in asperity (evidence of self-regulating process?)
- Need broad Rayleigh pulse but narrow supershear pulse (friction law?)

Supershear Transition via Multiple Diffractions

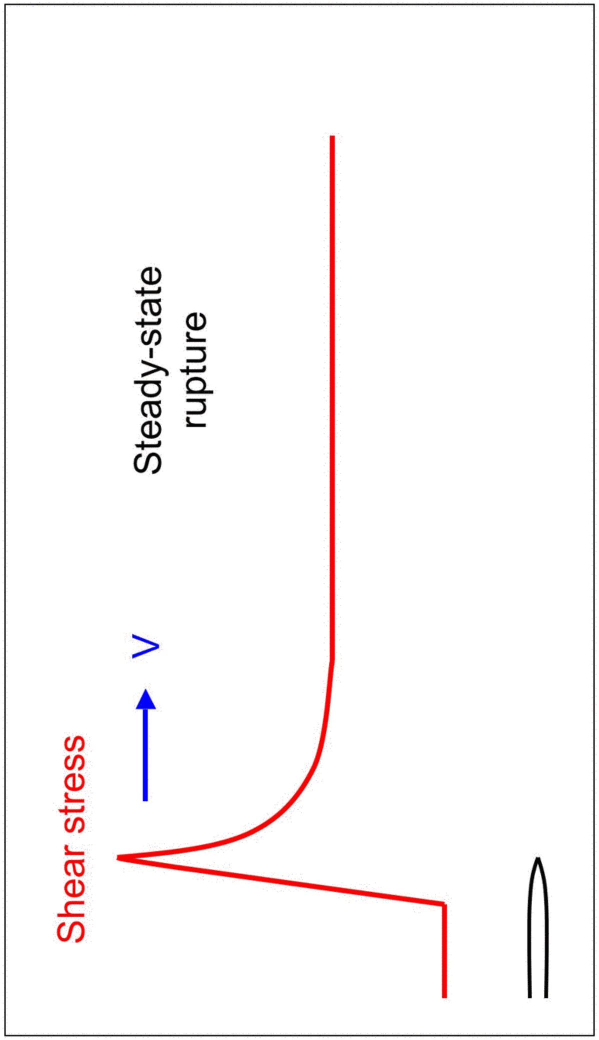
Early on, crack tips are close together and waves bounce around between them
(they act both as sources and diffractors)

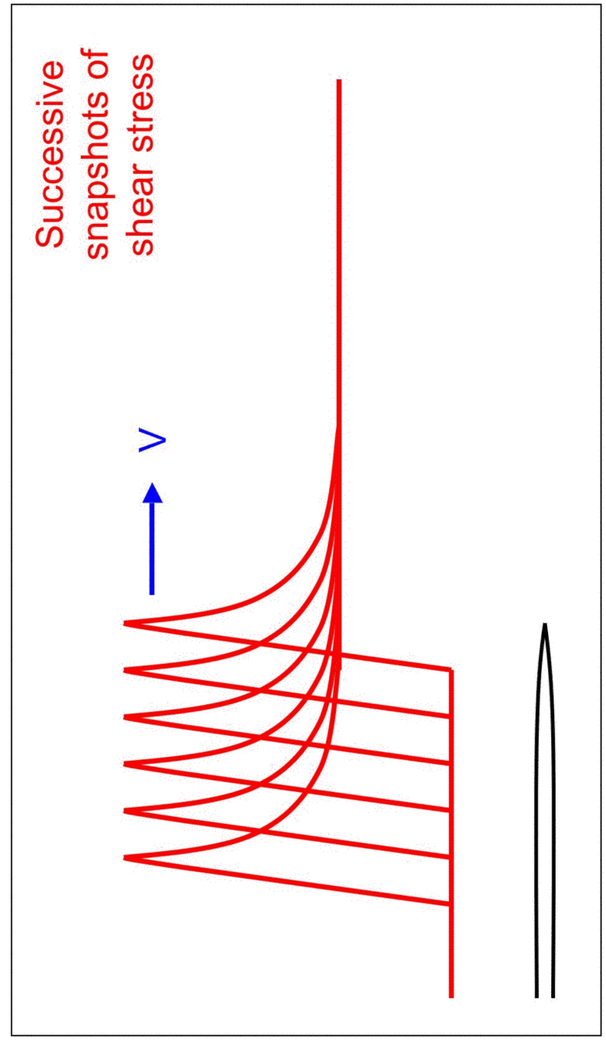


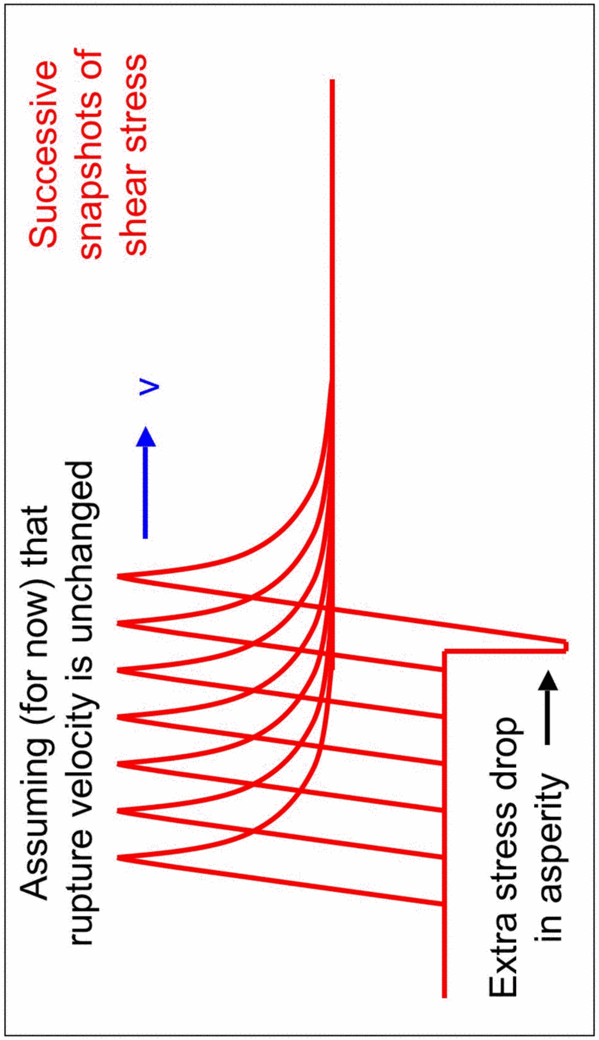
Multiple Diffractions Between Crack Tips

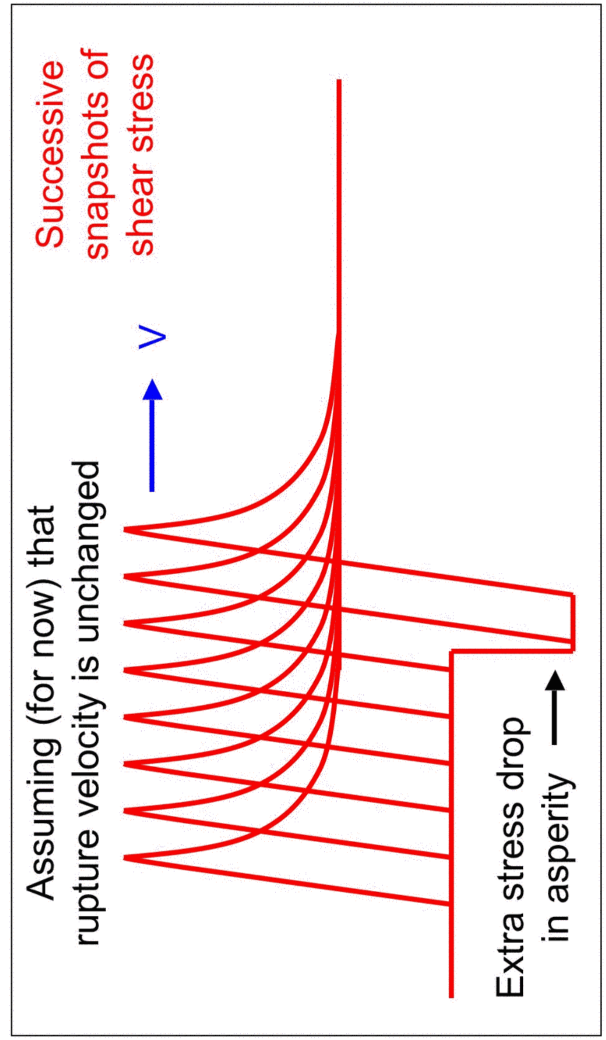


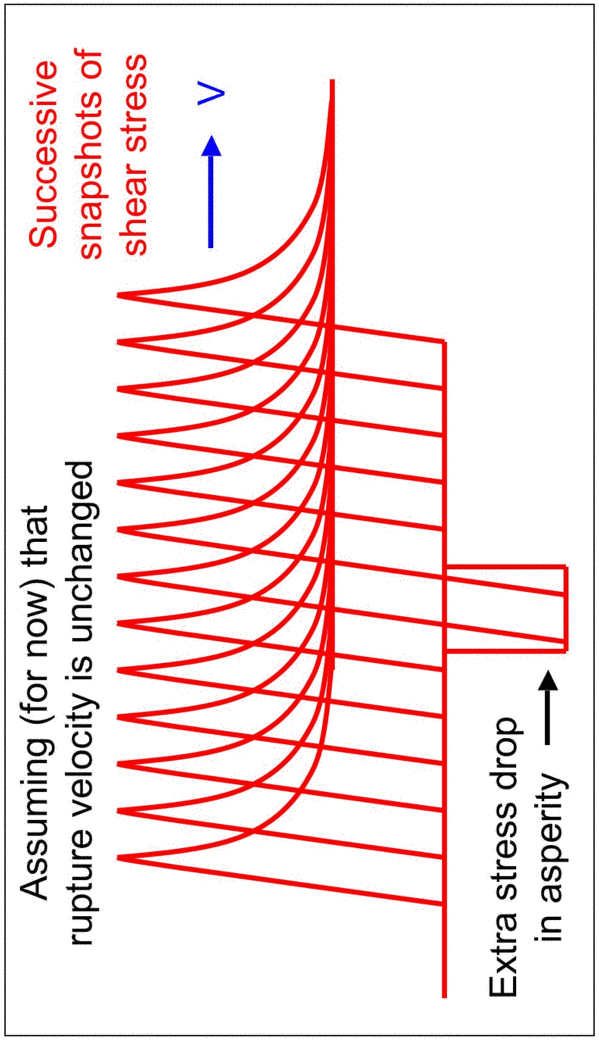
[Burridge, 1973; Andrews, 1976]

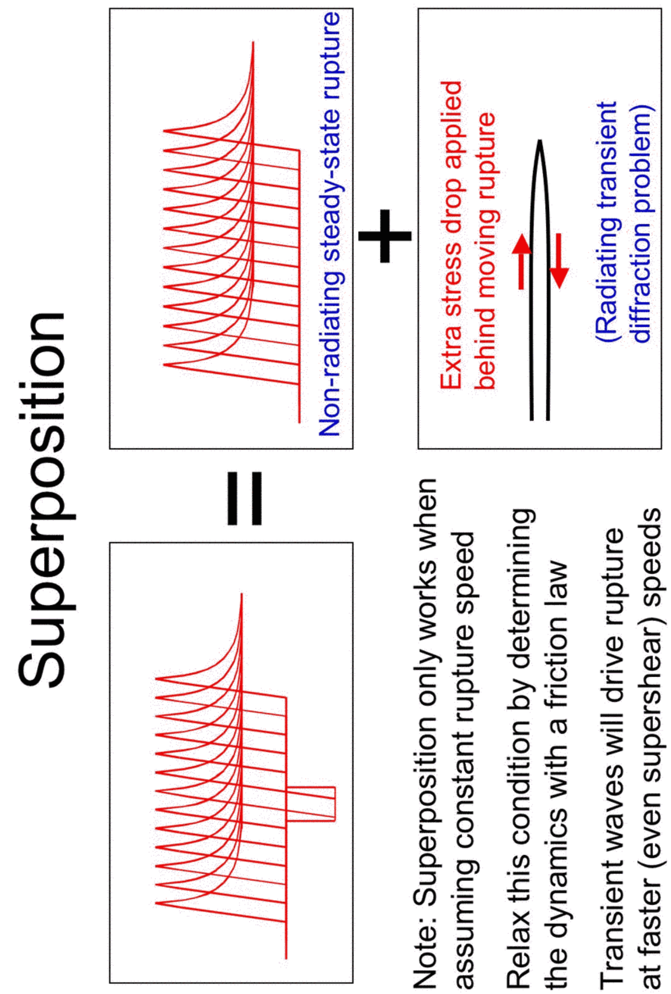

Shear stress
V
Steady-state
rupture

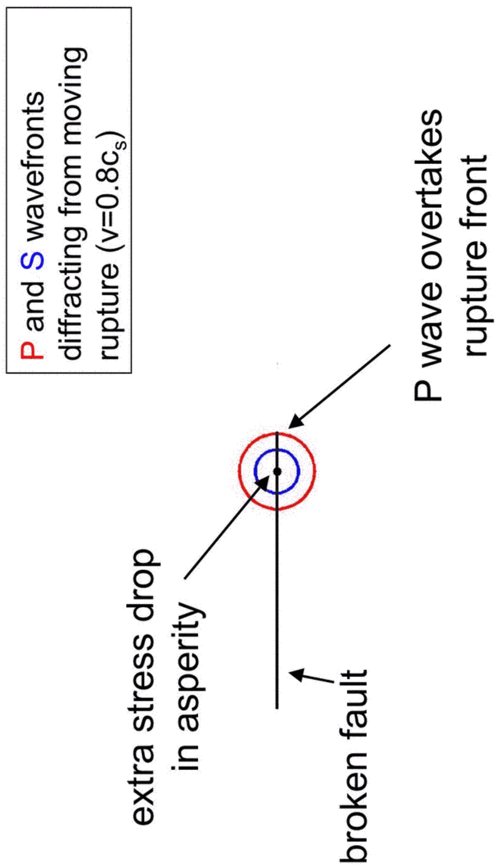

Successive
snapshots of
shear stress
V

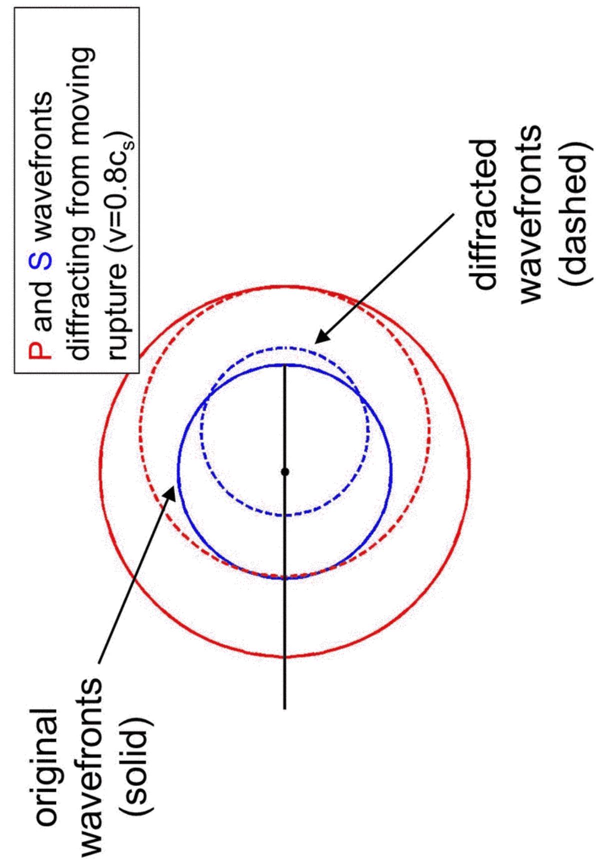

Successive snapshots of shear stress
Assuming (for now) that rupture velocity is unchanged
v
Extra stress drop in asperity

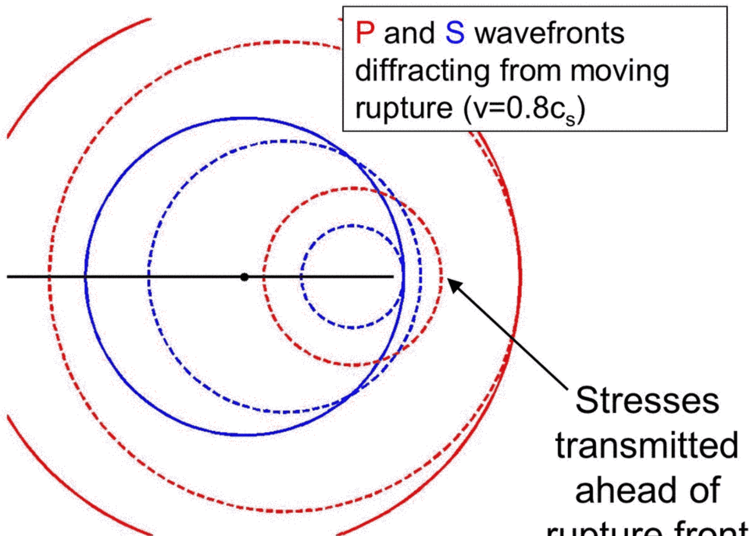

Successive snapshots of shear stress
Assuming (for now) that rupture velocity is unchanged
V
Extra stress drop in asperity


Successive snapshots of shear stress
V
Assuming (for now) that rupture velocity is unchanged
Extra stress drop in asperity

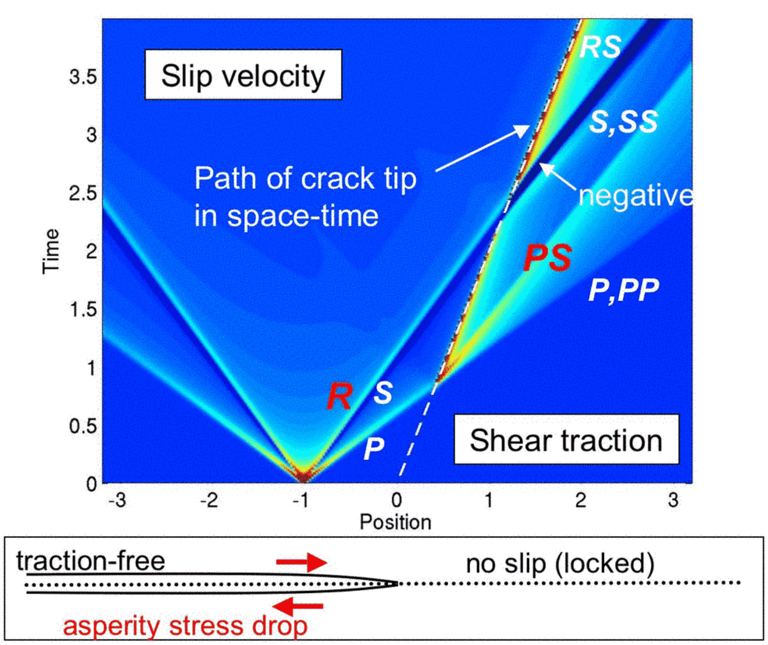

Superposition
Non-radiating steady-state rupture
Extra stress drop applied behind moving rupture
(Radiating transient diffraction problem)
Note: Superposition only works when assuming constant rupture speed
Relax this condition by determining the dynamics with a friction law
Transient waves will drive rupture at faster (even supershear) speeds


P and S wavefronts diffracting from moving rupture (v=0.8c$_s$)
P wave overtakes rupture front
extra stress drop in asperity
broken fault

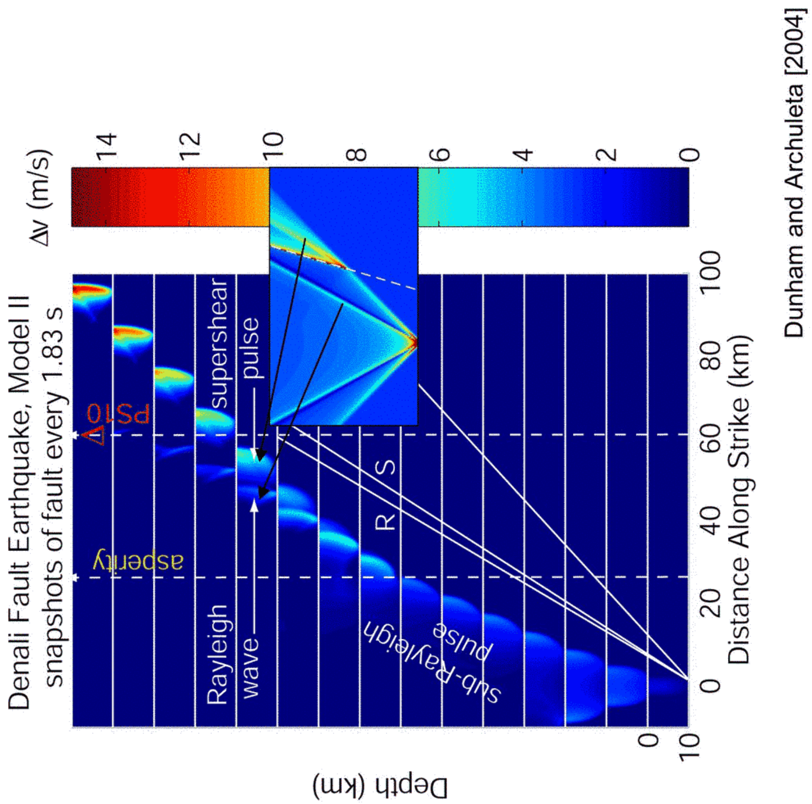

P and S wavefronts diffracting from moving rupture (v=0.8c$_s$)
diffracted wavefronts (dashed)
original wavefronts (solid)



Stress Drop Behind Moving Crack



Dunham and Archuleta [2004]


Denali Fault Earthquake, Model II
snapshots of fault every 1.83 s
Δv (m/s)
0
2
4
6
8
10
12
14
supershear
pulse
Rayleigh
wave
sub-Rayleigh
pulse
asperity
PS10
R
S
Depth (km)
0
10
Distance Along Strike (km)
0
20
40
60
80
100
Dunham and Archuleta [2004]