High Frequency Ground Motion from Spontaneous Ruptures on Rough Faults

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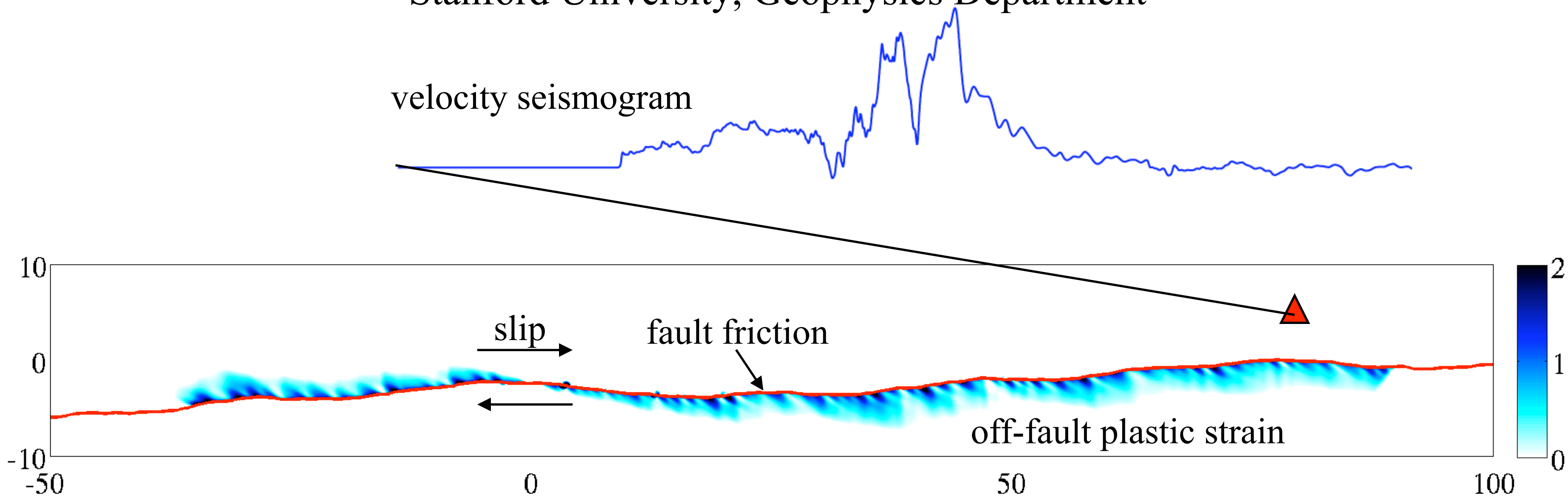

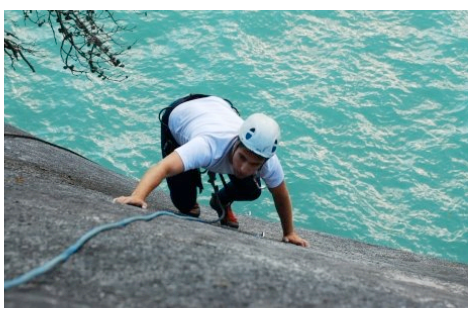

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Harvard University
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Harvard University
(now Stanford Business School)

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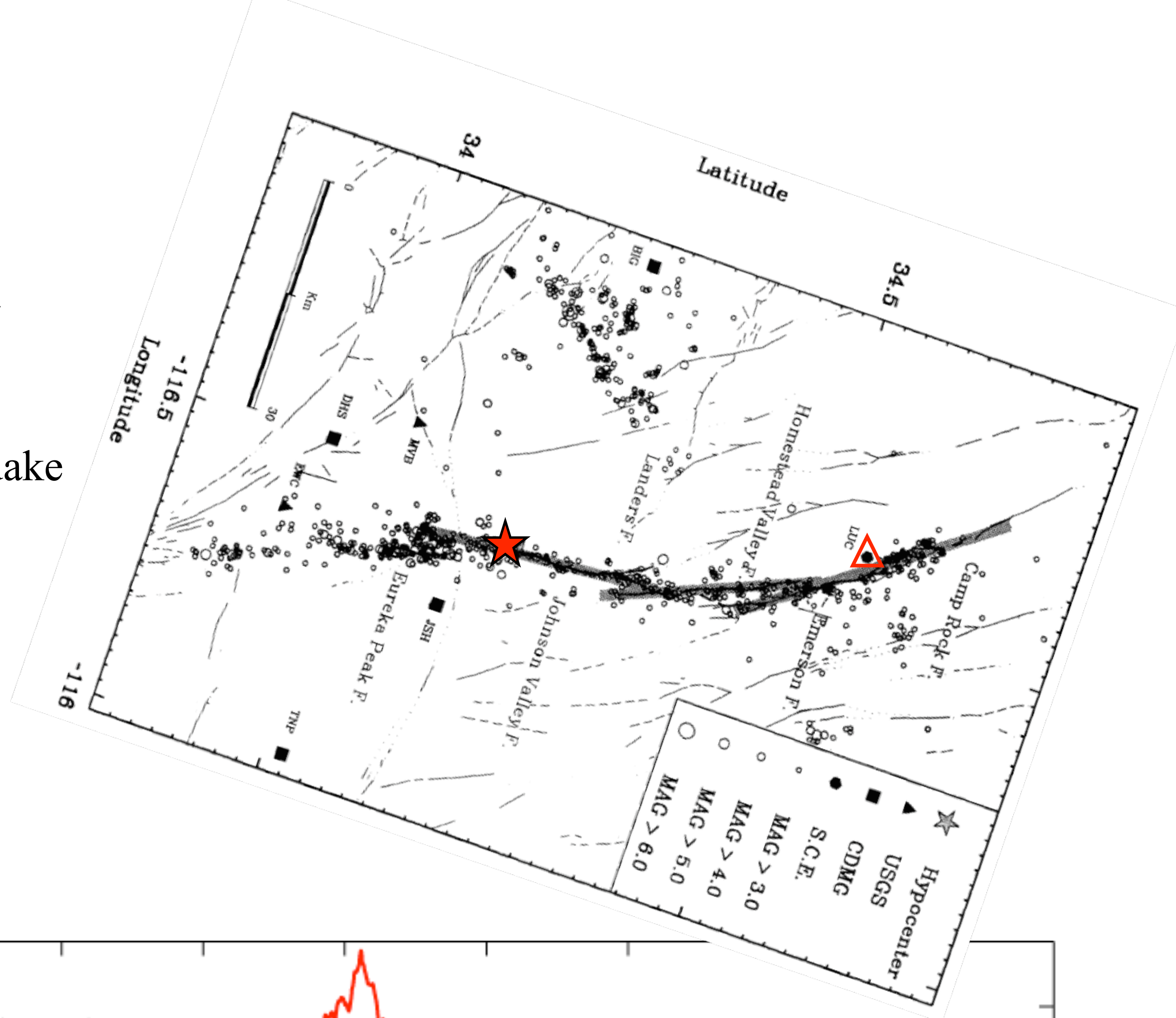
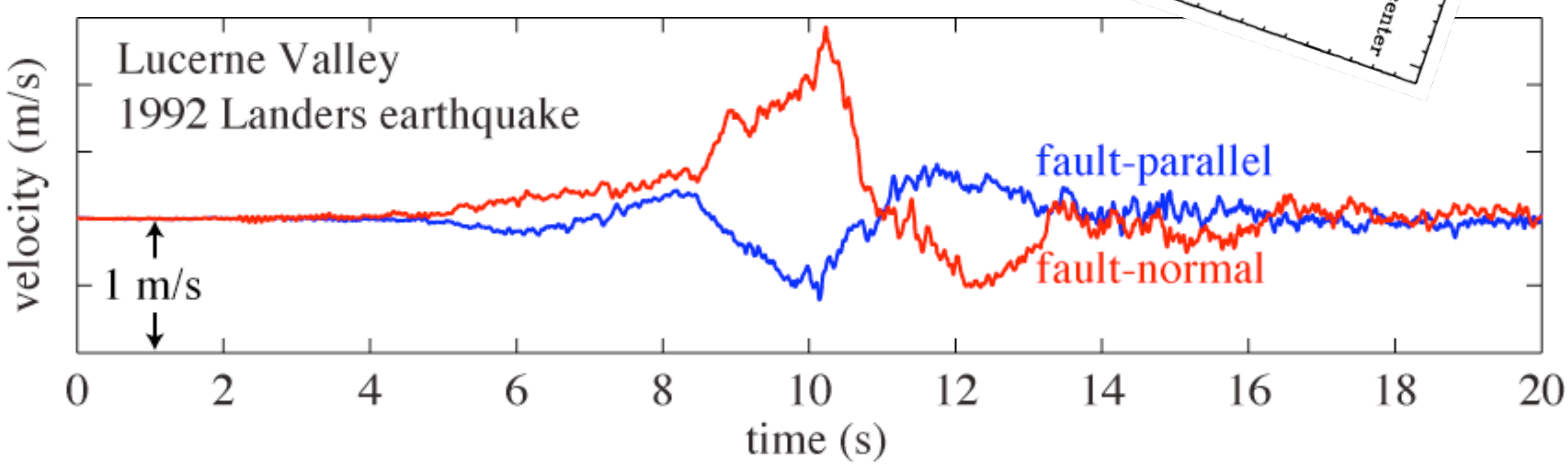
Stanford University

Jan Nordström
Uppsala University

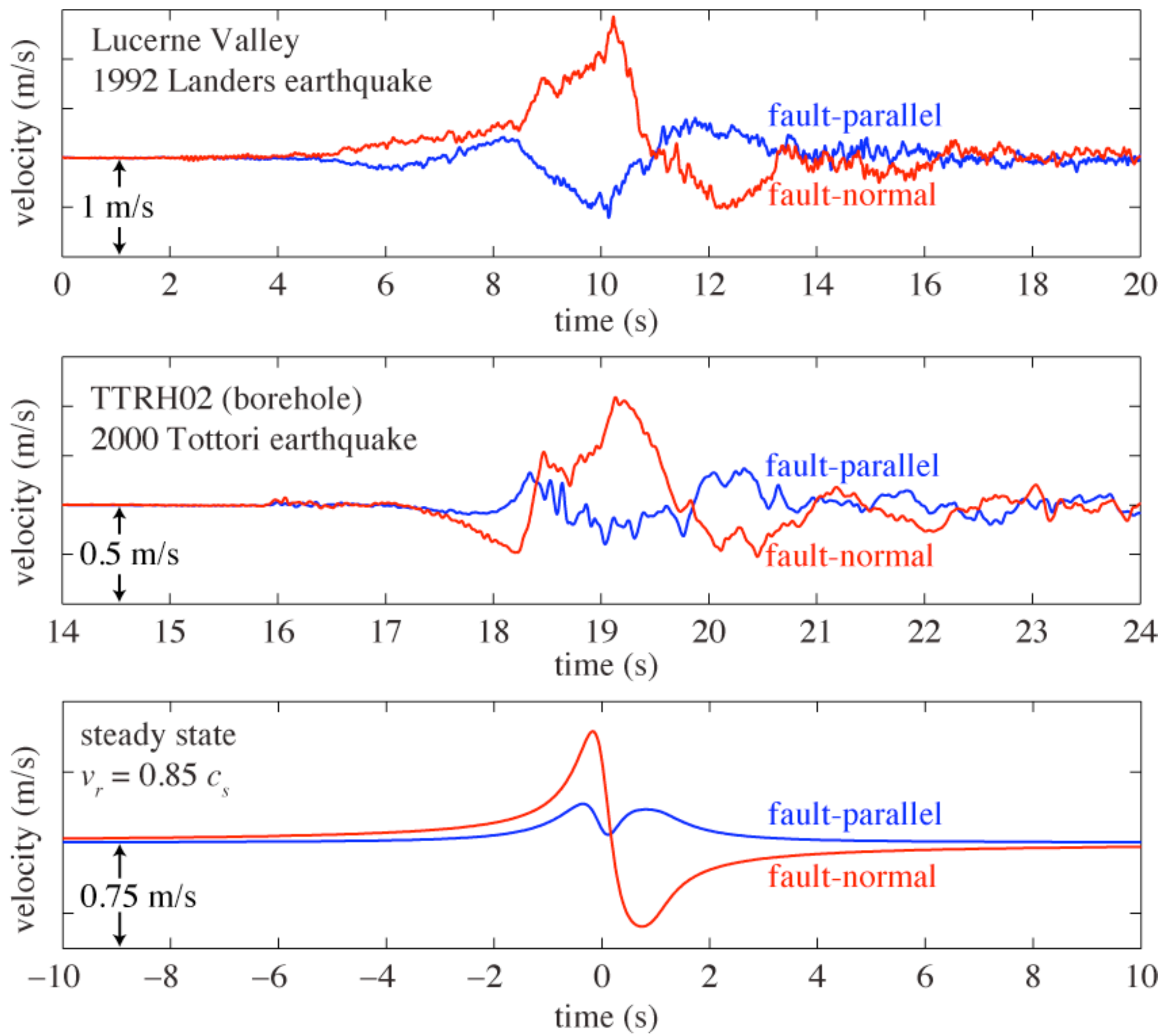
Near-Source Ground Motion

1992 M 7.3 Landers Earthquake
[Wald and Heaton, 1992]





Remarkably Coherent, Predictable Low Frequency Ground Motion



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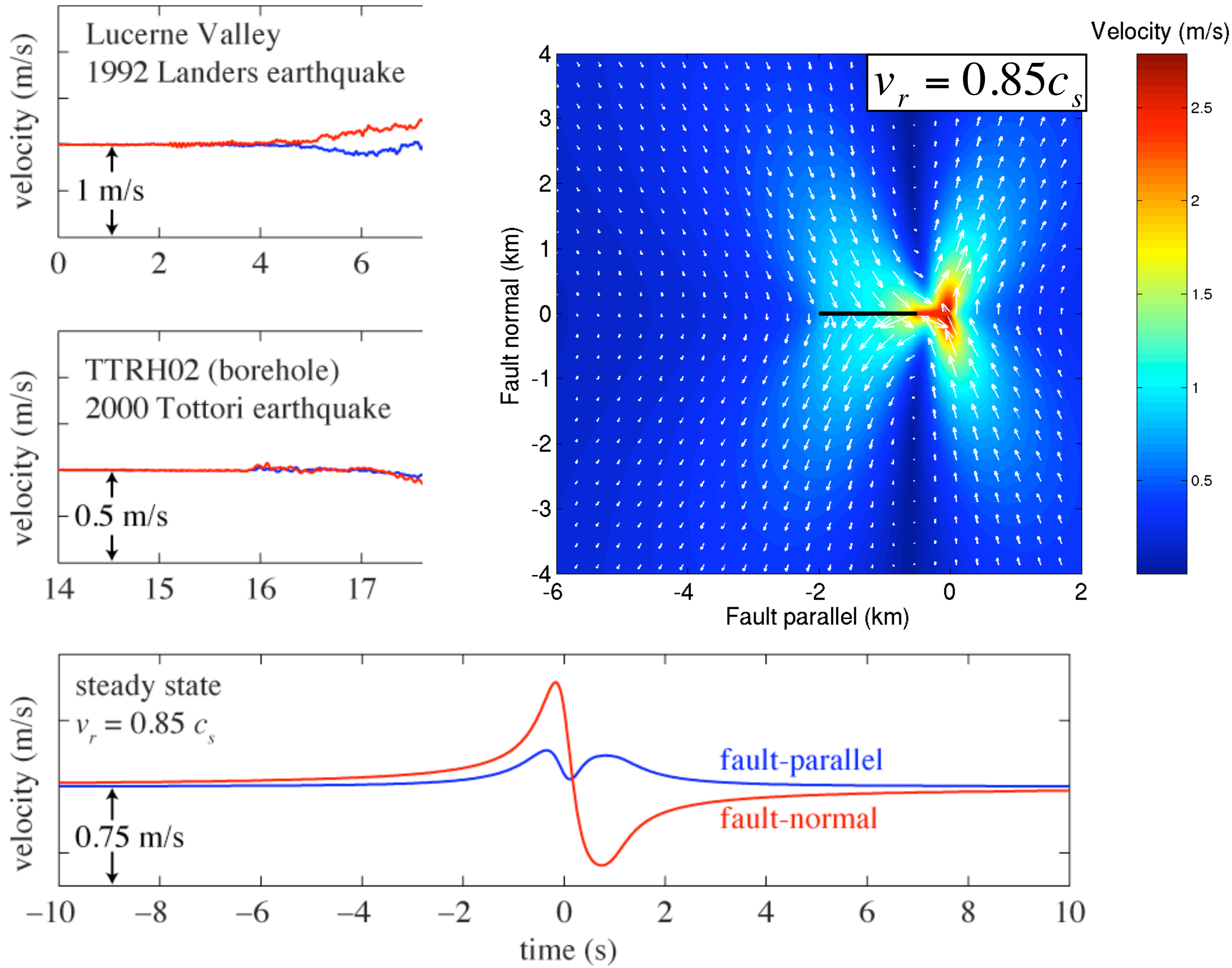

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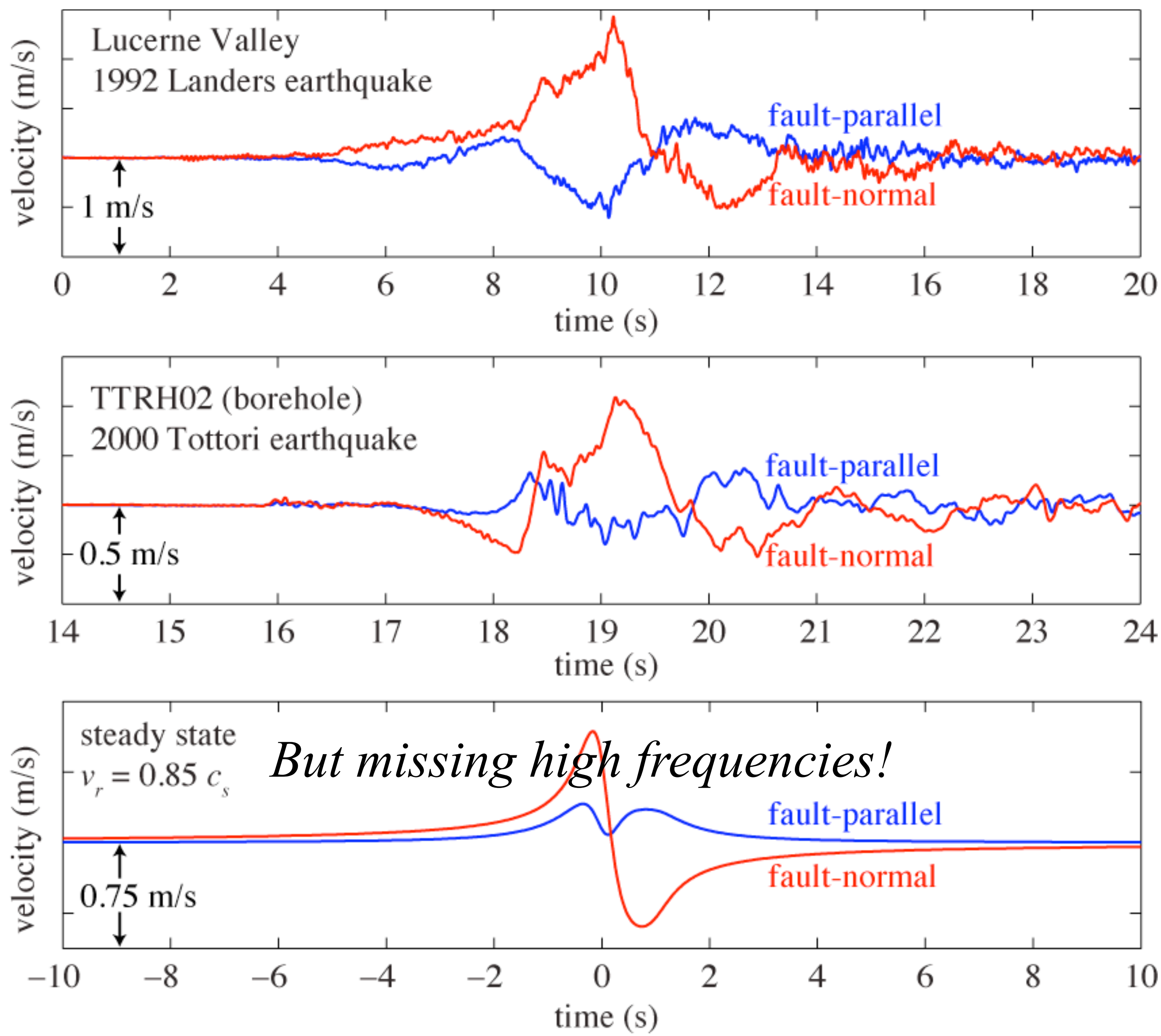
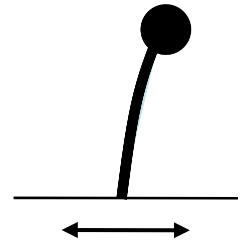


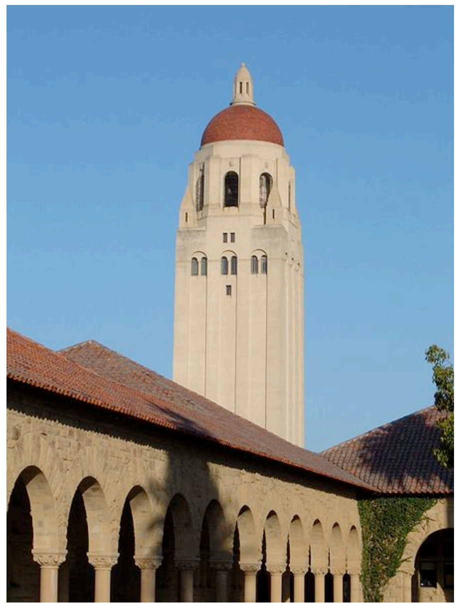
Building Response



force on base $\propto a_{\text{ground}}(t)$

Natural period:
T (s) ~ (number of stories)/10

Empire State Building
$T \sim 10$ s



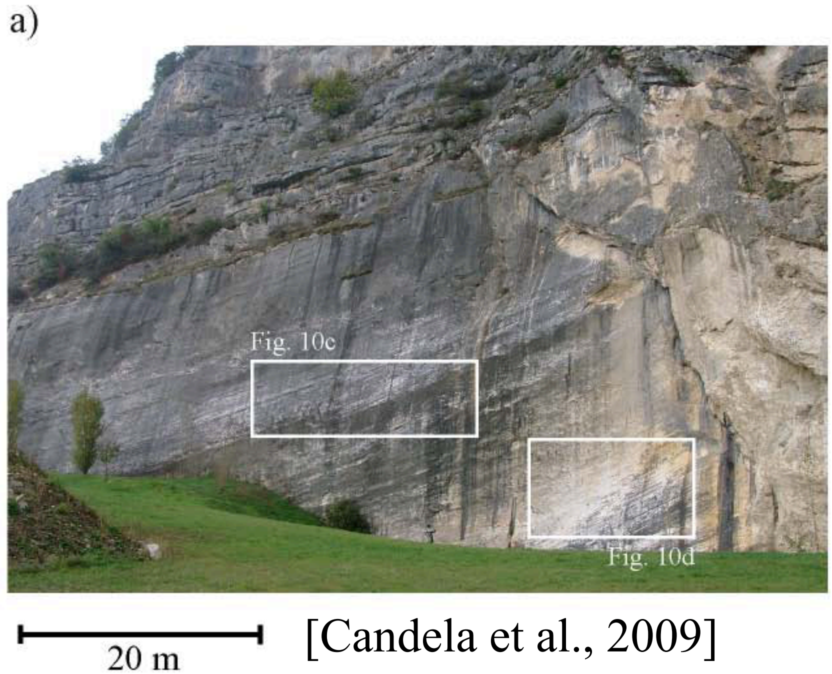
Hoover Tower
$T \sim 1$ s

residential house
$T \sim 0.1$ s

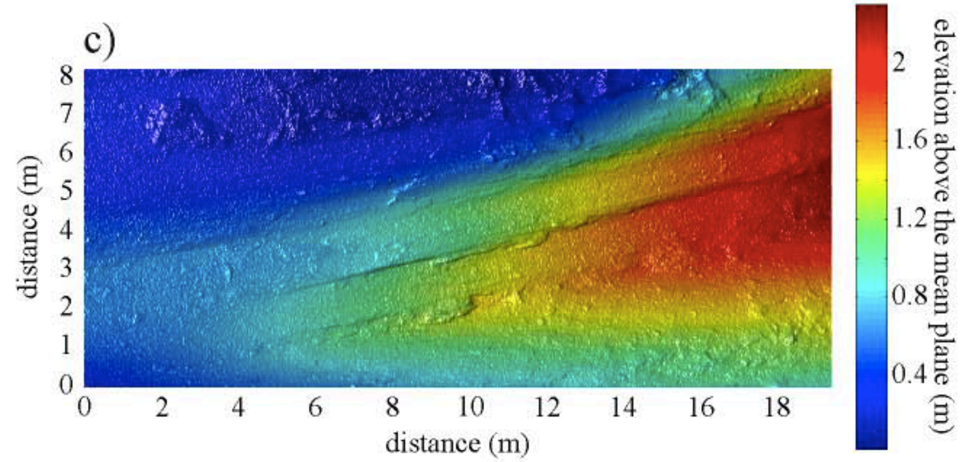
Must understand ground motion at $f \sim$ 1-10 Hz!

Incoherent high frequency ground motion from both *scattering* and *source complexity*

Geometrical Complexity and Roughness of Faults



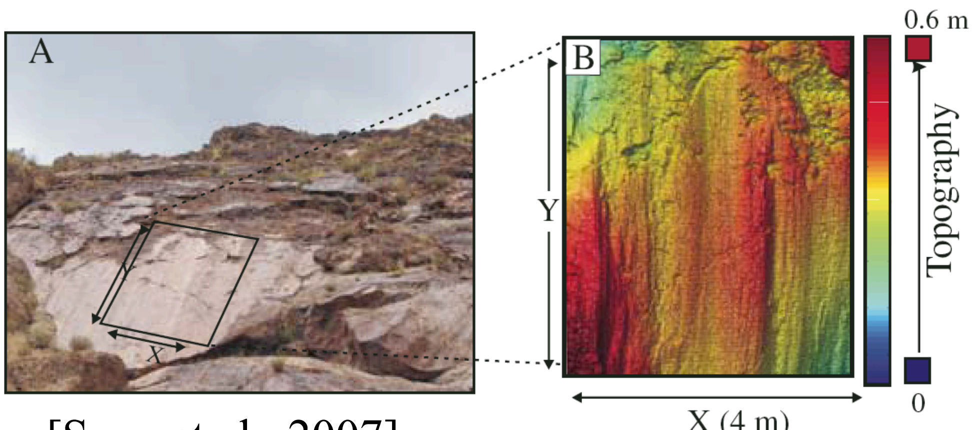
[Candela et al., 2009]



Roughness evident at all scales, faults are self-similar fractal surfaces

⇒ waves excited at all wavelengths (potential to explain why ground acceleration has flat power spectrum)

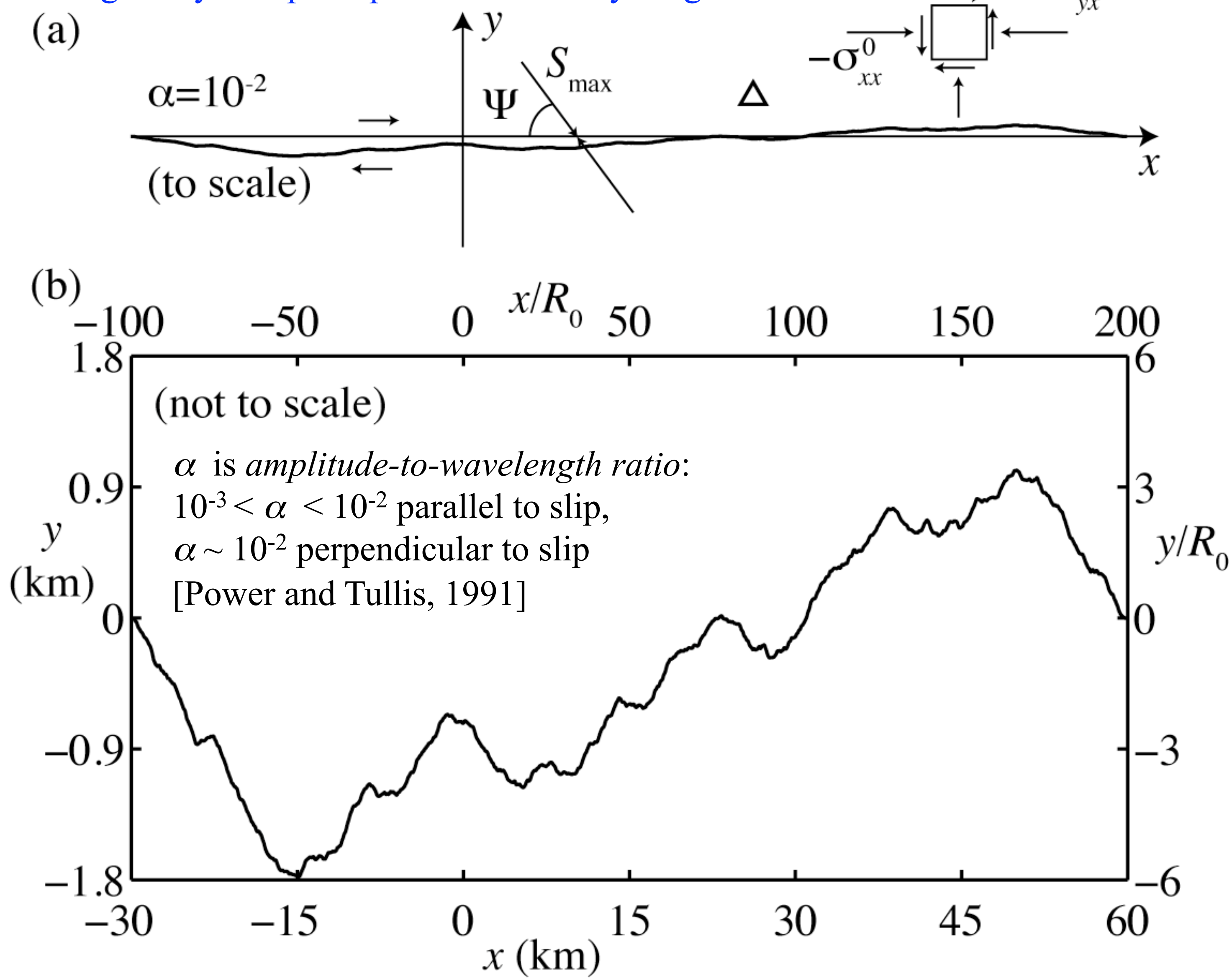
Note: 0.1-1 km roughness wavelengths ⇒ 1-10 Hz ground motion)



[Sagy et al., 2007]

Self-Similar Fractal Profiles

spatially uniform loading (and friction law parameters)
⇒ all irregularity in rupture process caused by roughness



Stress Perturbations from Slip on Rough Faults

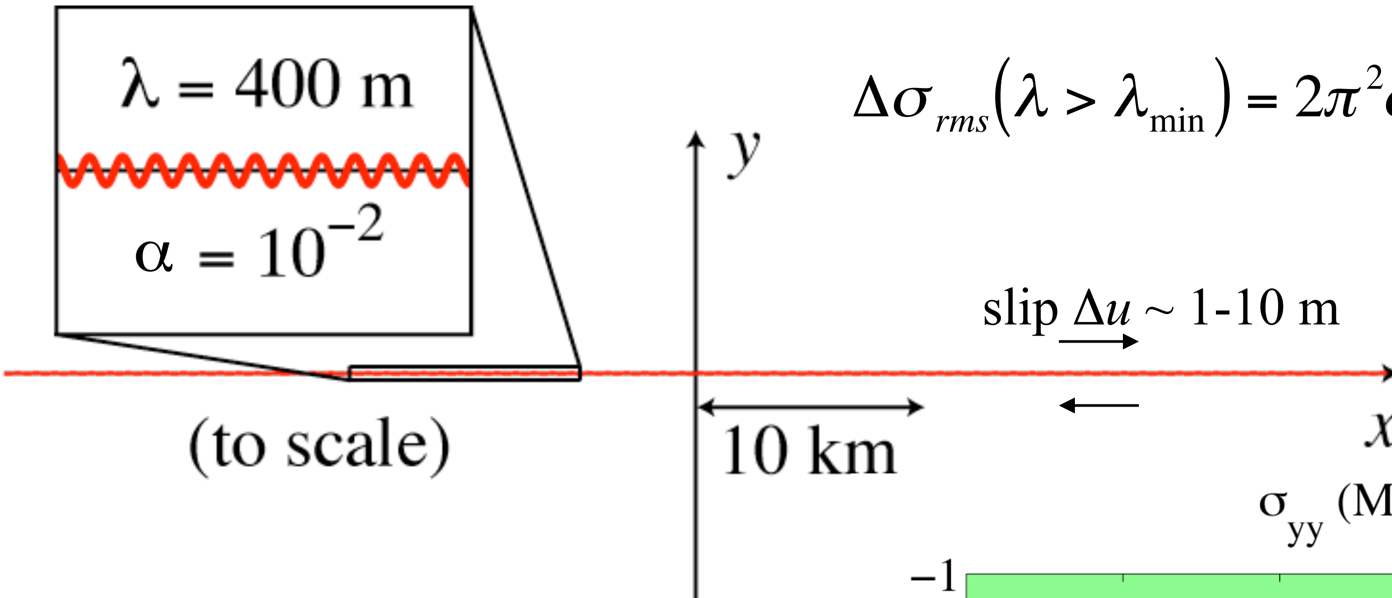
(slip Δu << roughness wavelength λ)

(possibility of fault opening, inelastic off-fault material response)

Most interesting for large slip (long faults)

$$\Delta\sigma_{rms}(\lambda > \lambda_{min}) = 2\pi^2\alpha \frac{G}{1-\nu}\frac{\Delta u}{\lambda_{min}}$$

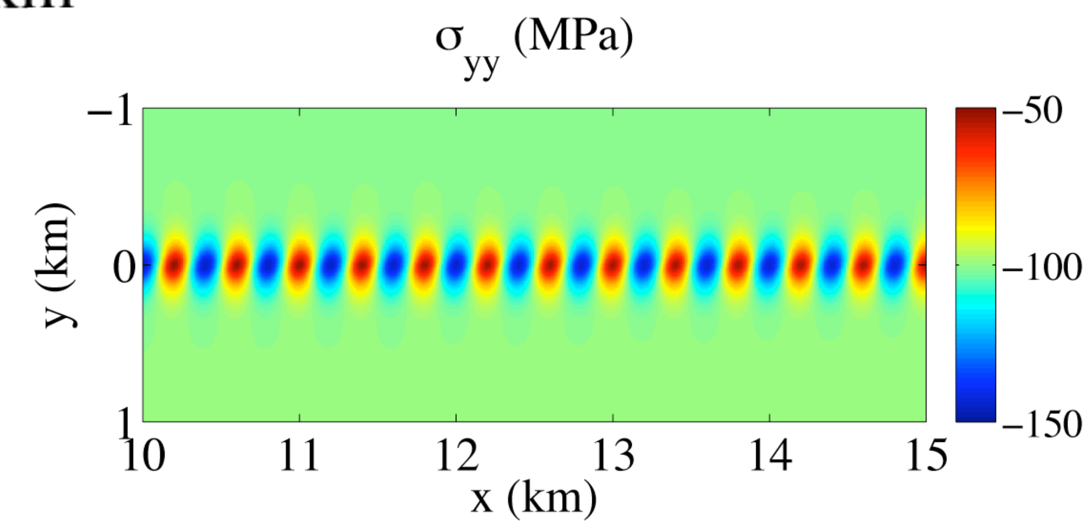
short wavelengths



Feedback into rupture process through friction law:

$$\tau = f(V,\psi)\sigma$$

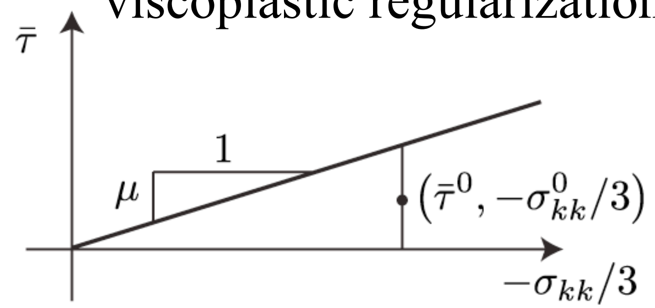
(strongly rate-weakening steady state with slip law evolution)



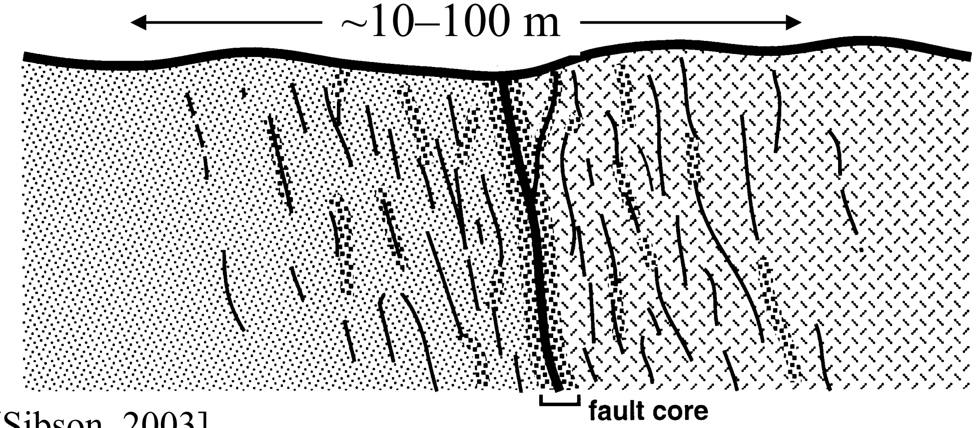
As studied in static case by Chester and Chester [2000]; Dieterich and Smith [2009]

Inelastic Off-fault Response

(a) Drucker-Prager plasticity with viscoplastic regularization

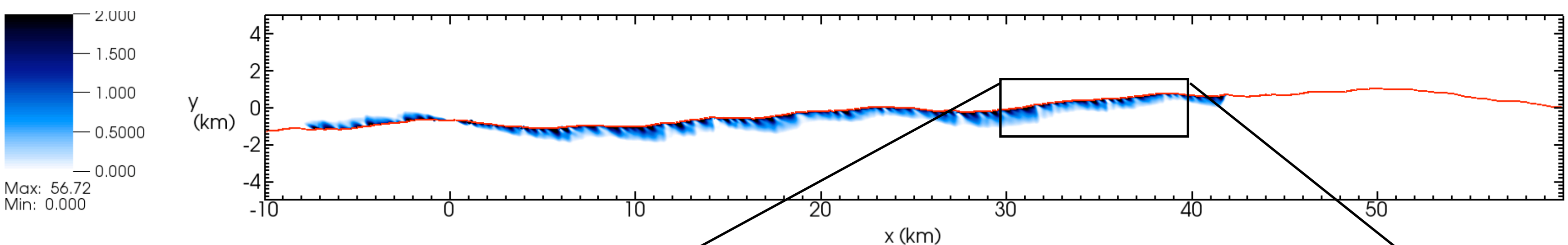


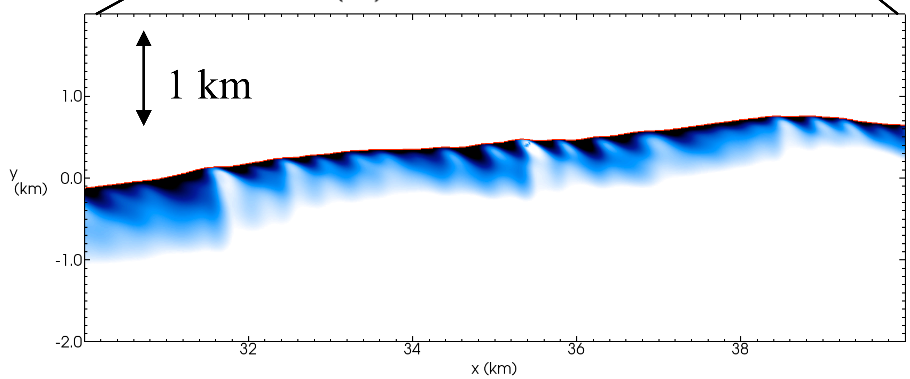
damage zones and aftershocks



[Sibson, 2003]

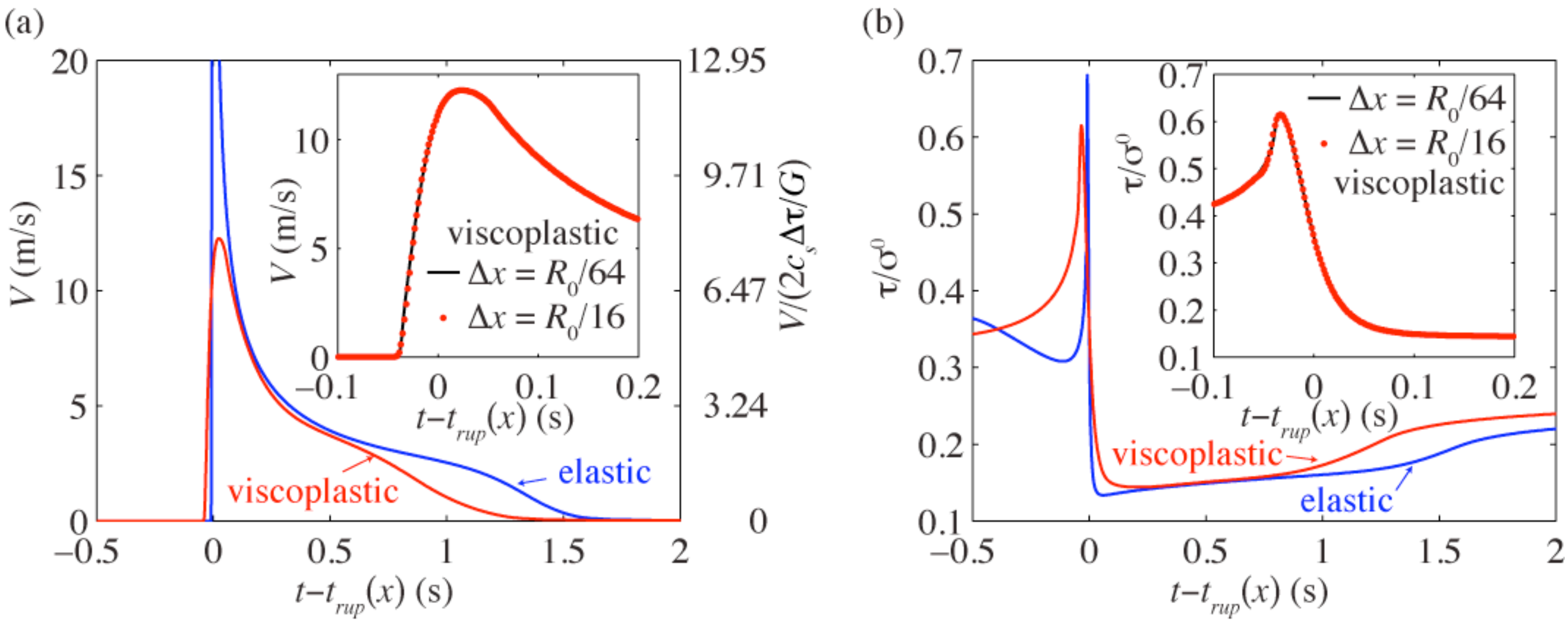
plastic strain



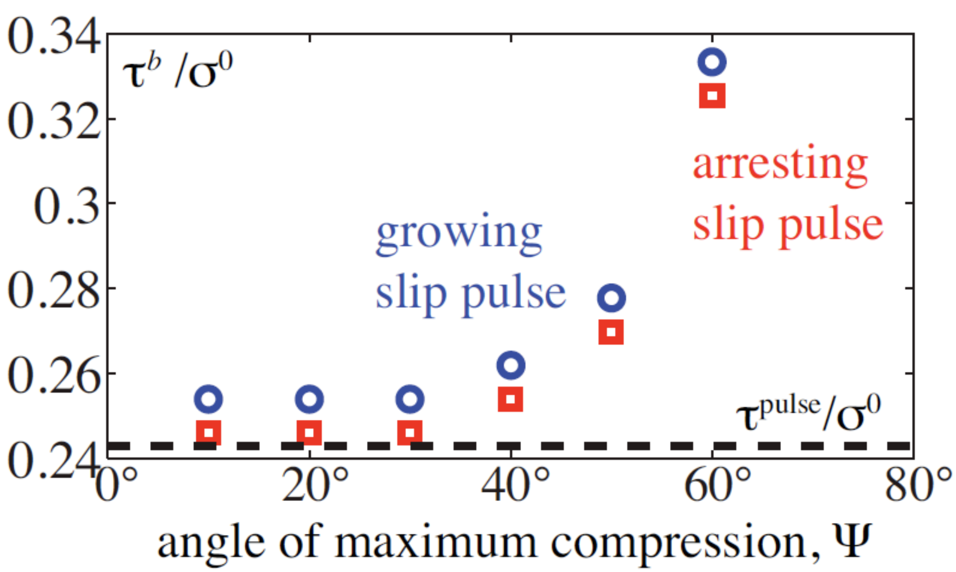


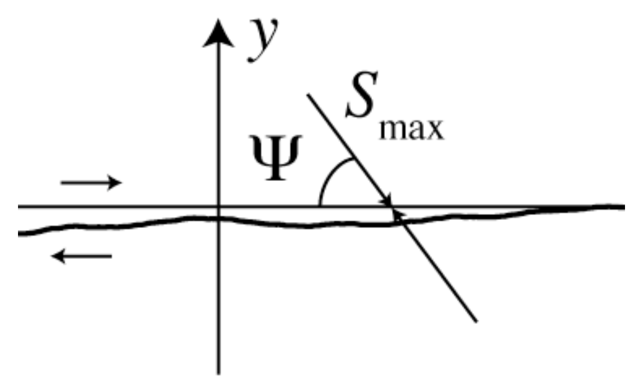
Off-fault plasticity limits stress perturbations and prevents fault opening (for sufficiently low cohesion)

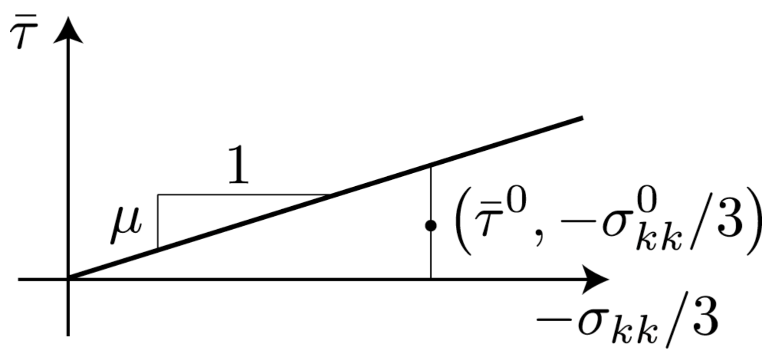
Ruptures Propagate as Slip Pulses at Low Background Stress Levels

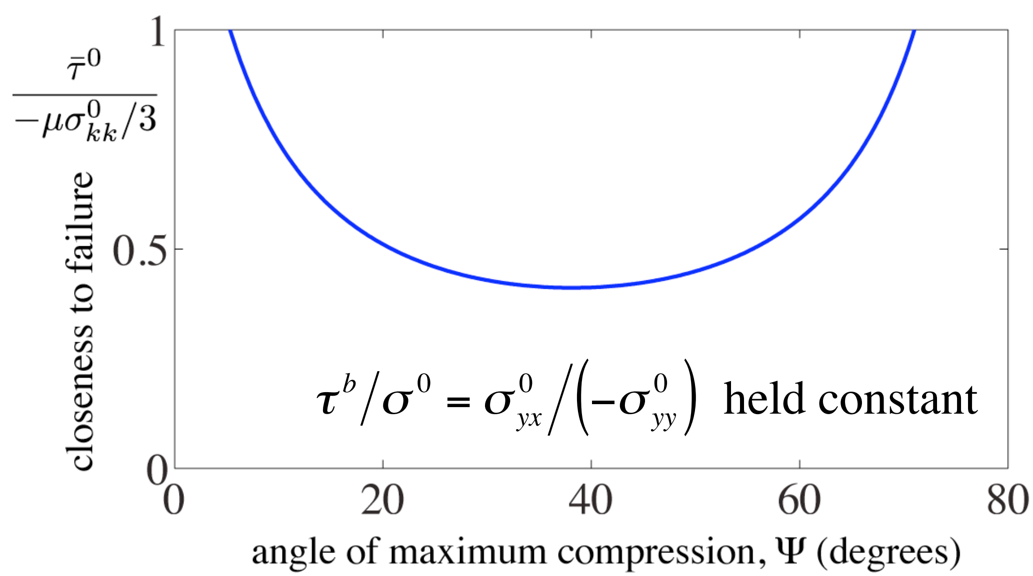


Plasticity Increases Critical Background Stress Level



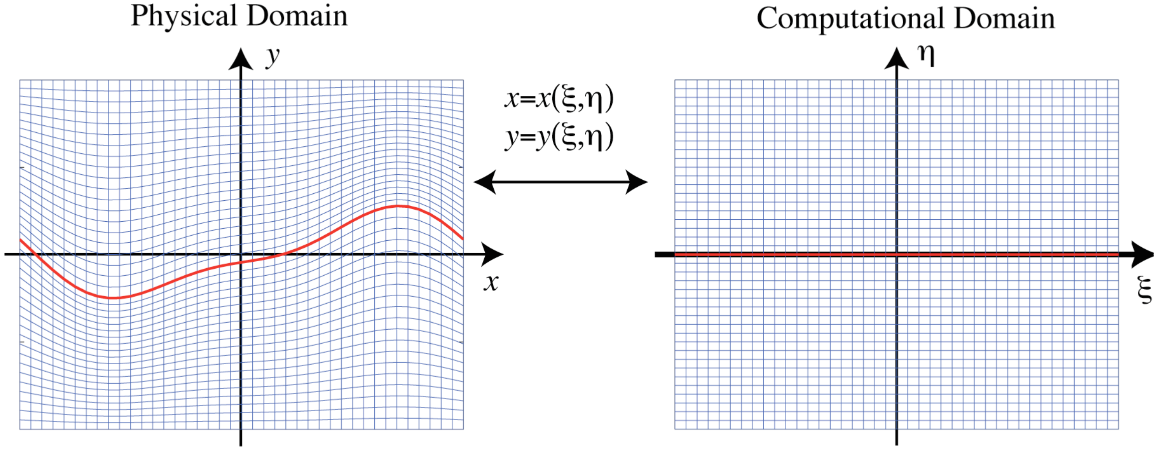


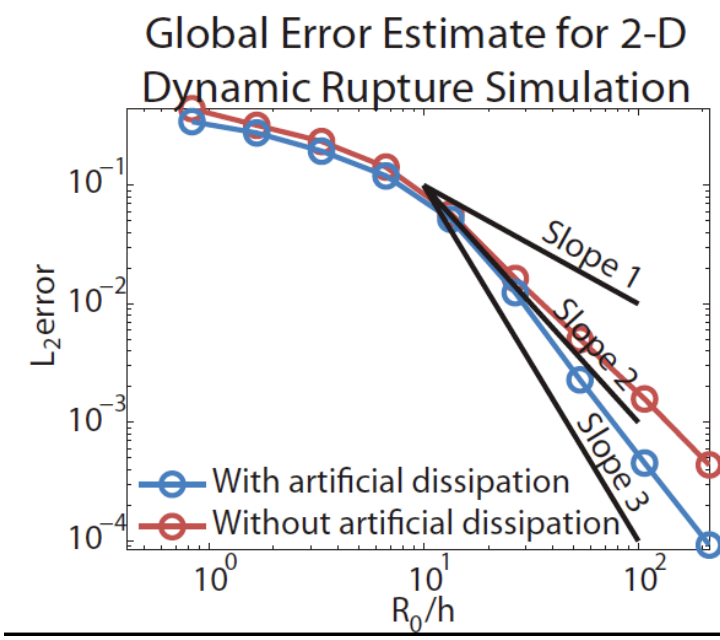


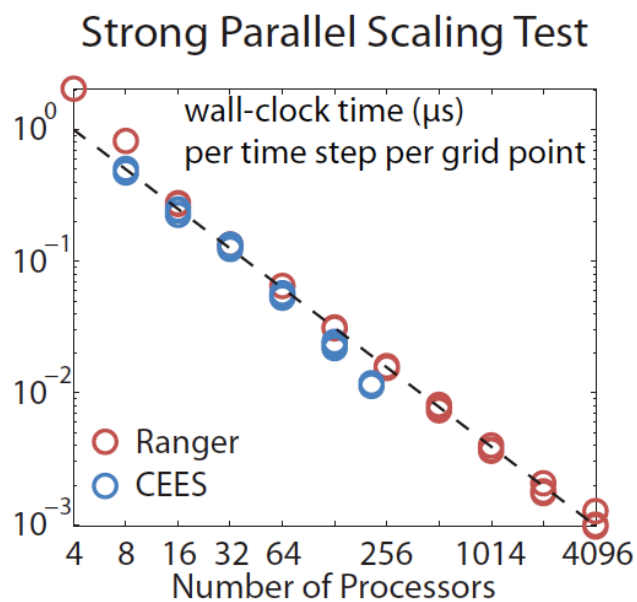


Numerical Method: Simultaneous Solution of Elastodynamics and Friction Law

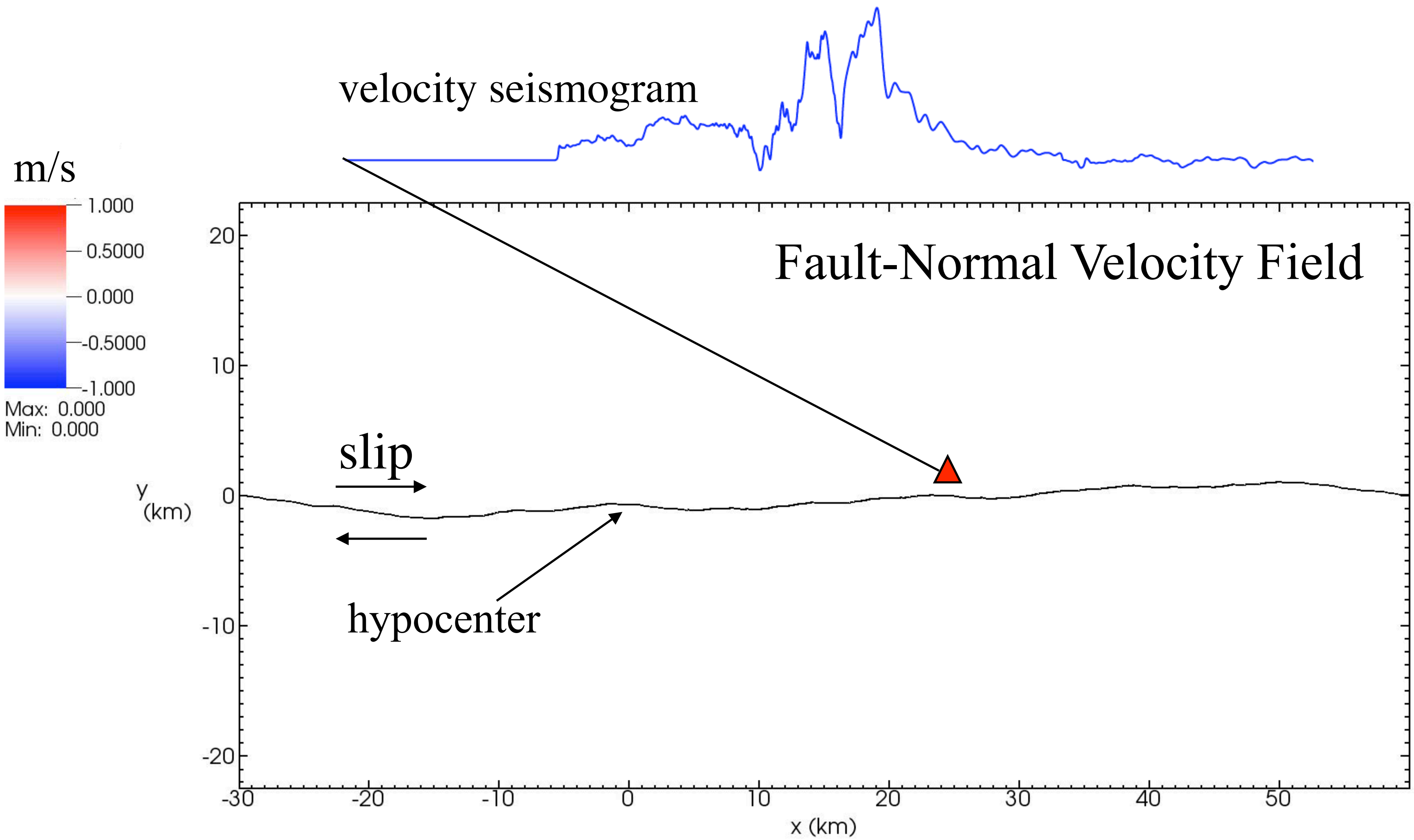
- Block-structured curvilinear meshes
- Artificial dissipation to control oscillations
- SBP+SAT finite differences
- Provably stable and high-order accurate

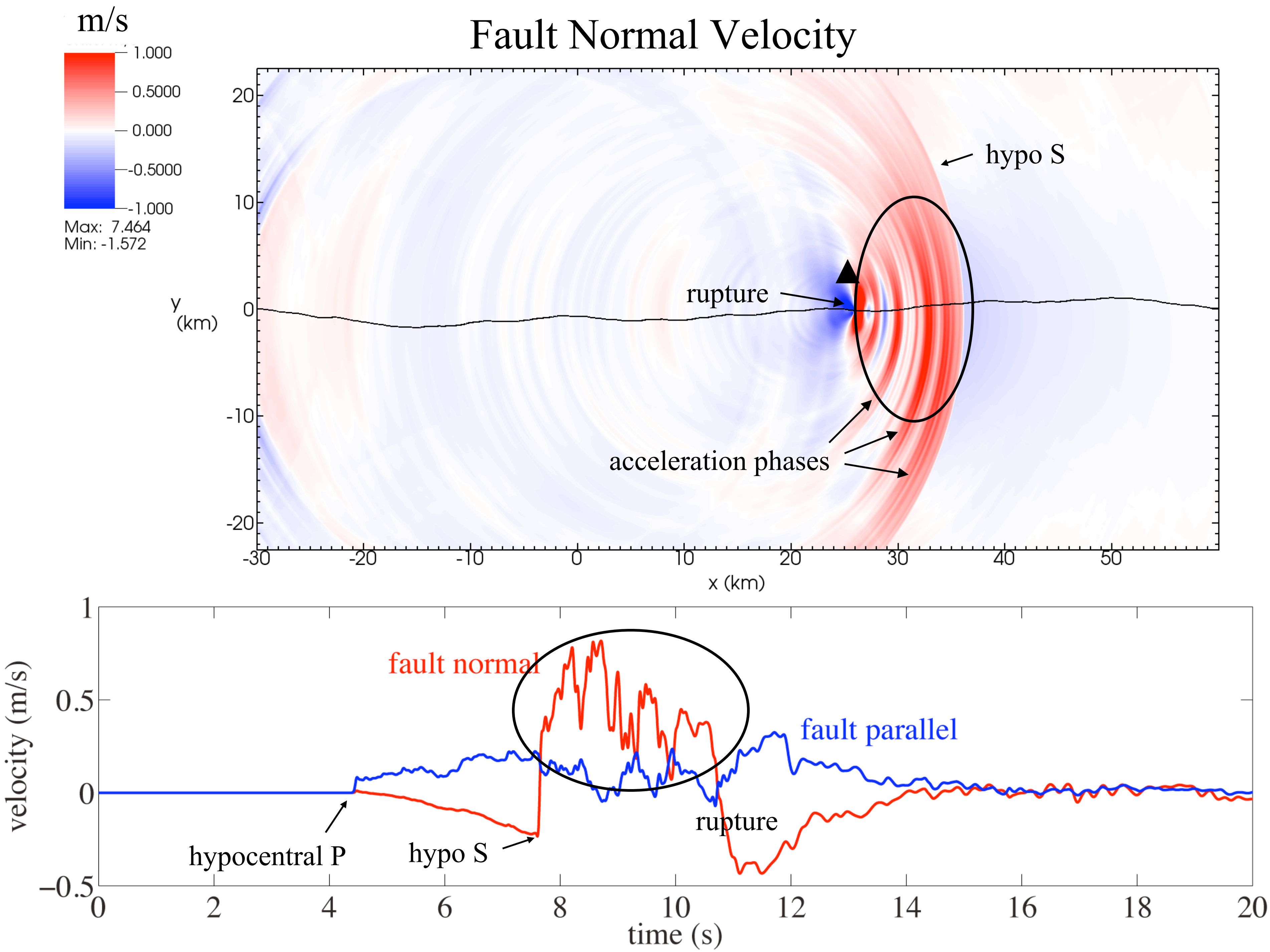




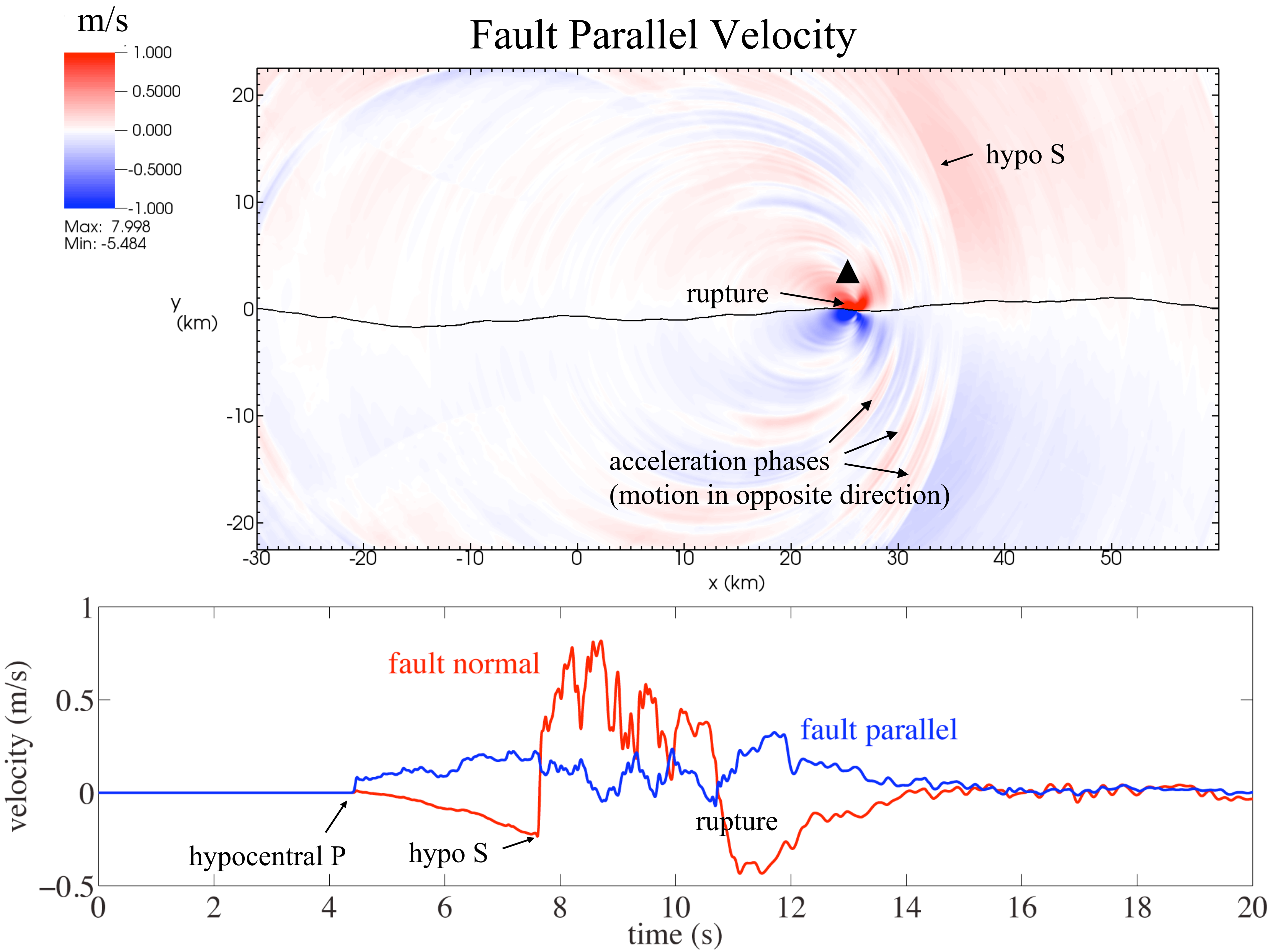


Incoherent High Frequency Waves from Irregular Propagation



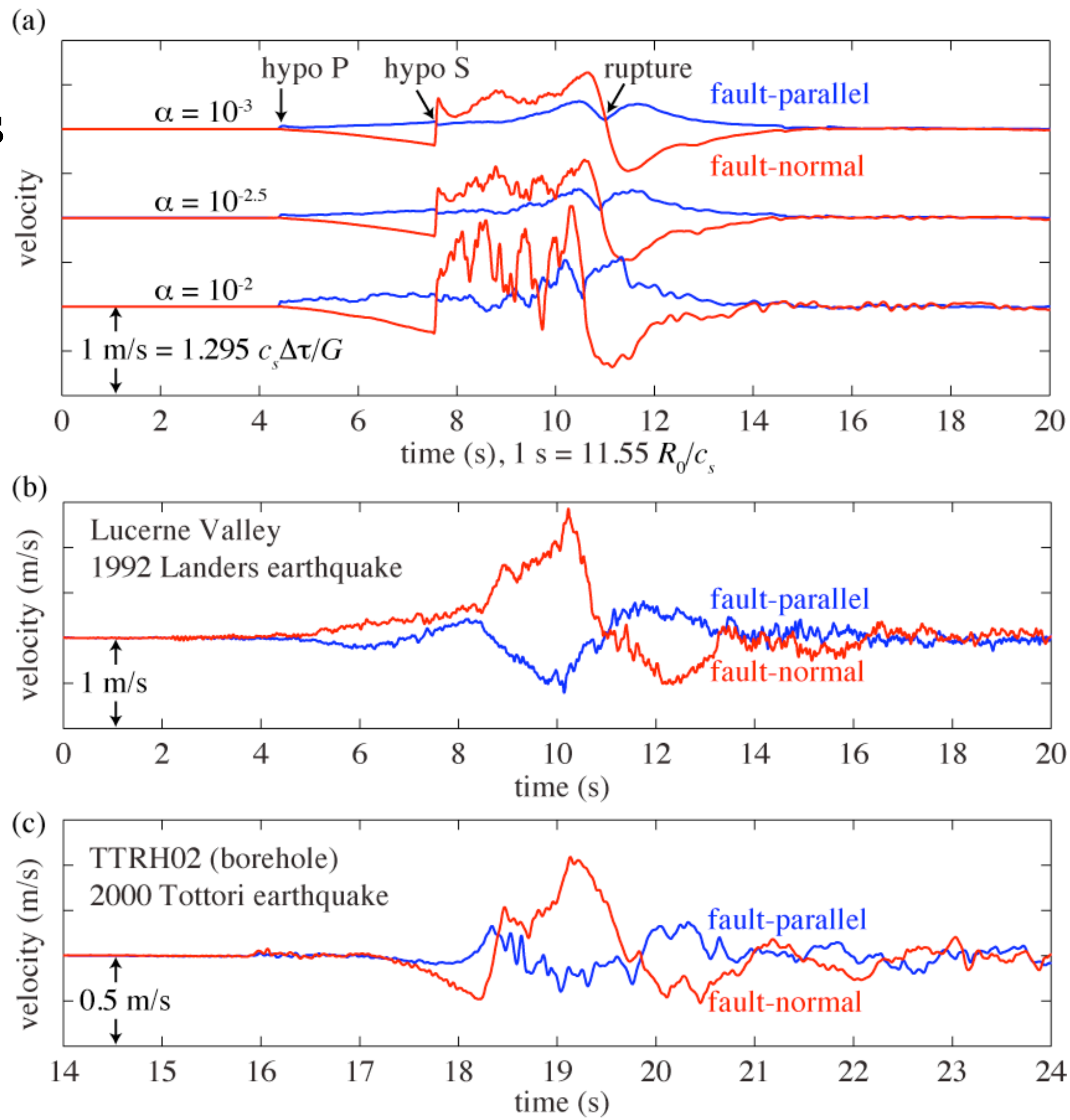


Fault Normal Velocity
m/s
1.000
0.5000
0.000
-0.5000
-1.000
Max: 7.464
Min: -1.572
hypo S
rupture
acceleration phases
y (km)
x (km)
fault normal
fault parallel
hypocentral P
hypo S
rupture
velocity (m/s)
time (s)



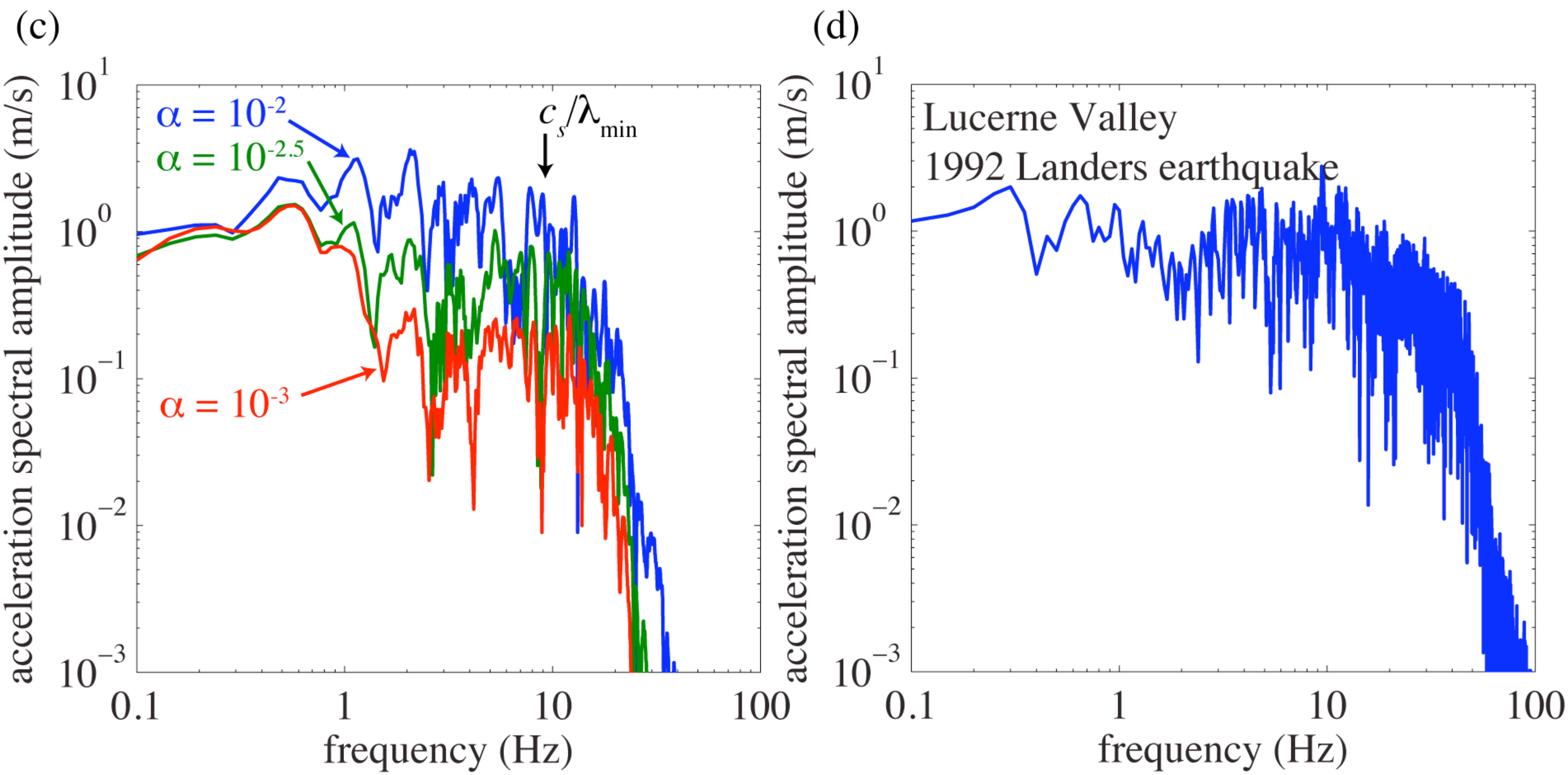
Fault Parallel Velocity
m/s
1.000
0.5000
0.000
-0.5000
-1.000
Max: 7.998
Min: -5.484
y (km)
x (km)
hypo S
rupture
acceleration phases
(motion in opposite direction)
fault normal
fault parallel
velocity (m/s)
time (s)
hypocentral P
hypo S
rupture

Velocity Seismograms



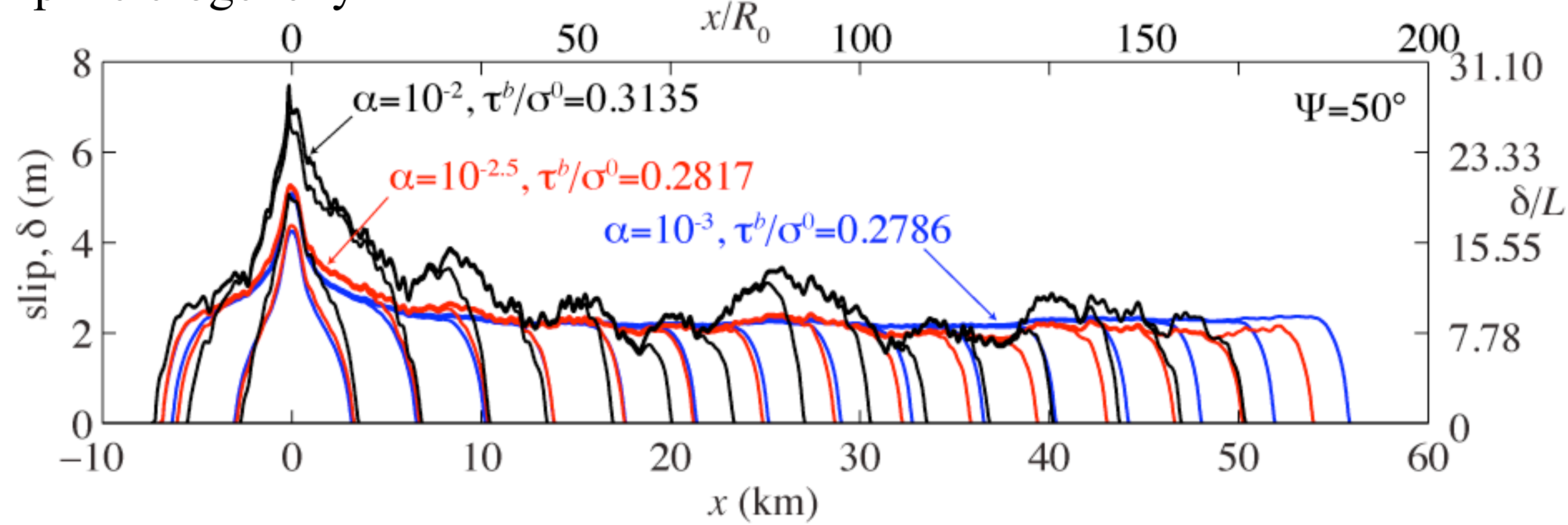
Acceleration Spectra

…acceleration time histories are, to a very good approximation, band-limited white Gaussian noise… [Hanks and McGuire, 1981]

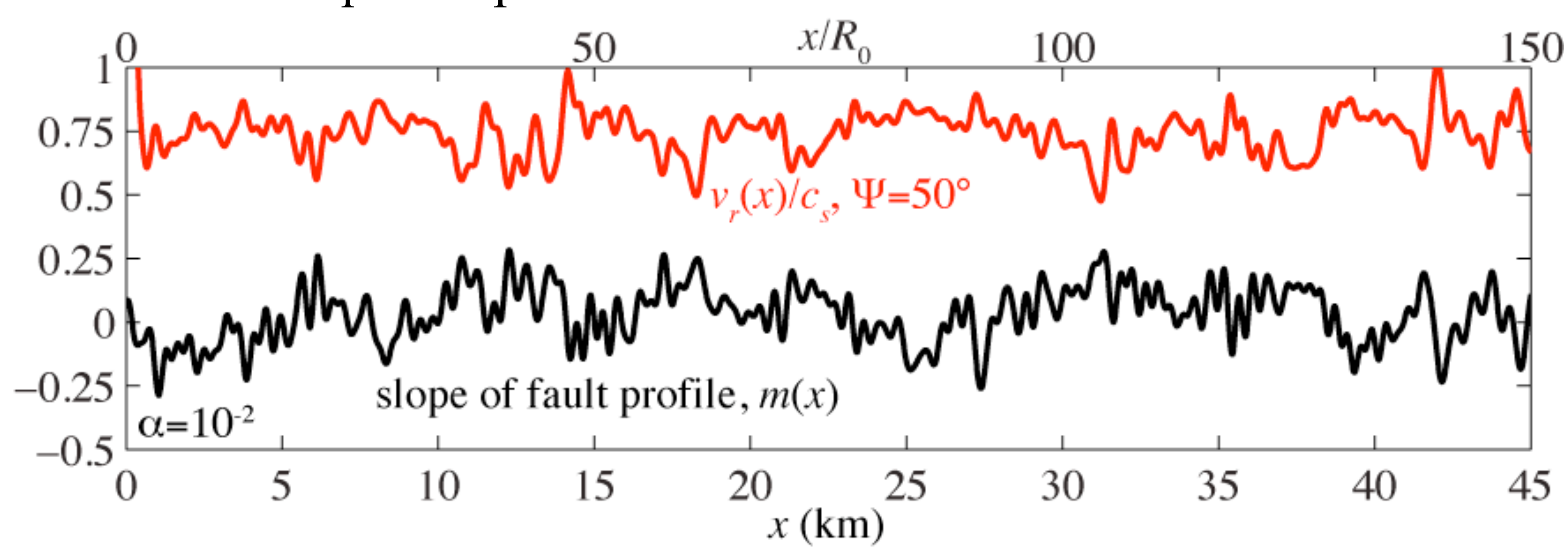


Sources of Incoherence Correlated with Local Fault Geometry

(1) Slip Heterogeneity



(2) Variations in Rupture Speed

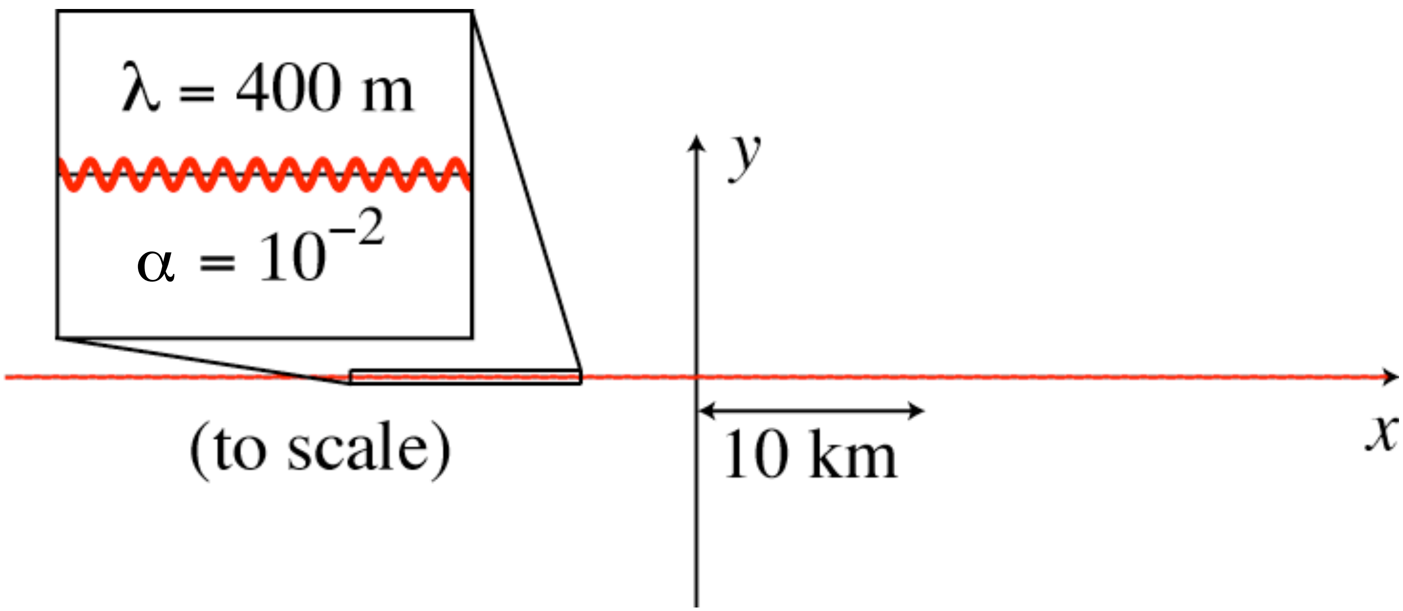


Additional Resistance to Slip ("Roughness Drag"): A *Second Order* Effect

Well known for glaciers (Stokes flow) [Nye, 1970], but unknown for faults.
Estimate rms force per unit area of top half-space on bottom half-space, *in addition to frictional resistance*:

$$\tau^{drag} \sim 8\pi^2\alpha^2 \frac{G}{1-\nu}\frac{\Delta u}{\lambda_{\min}}$$

Comparable to frictional resistance, even for $\alpha \sim 10^{-3}$, provided material response remains ideally elastic.



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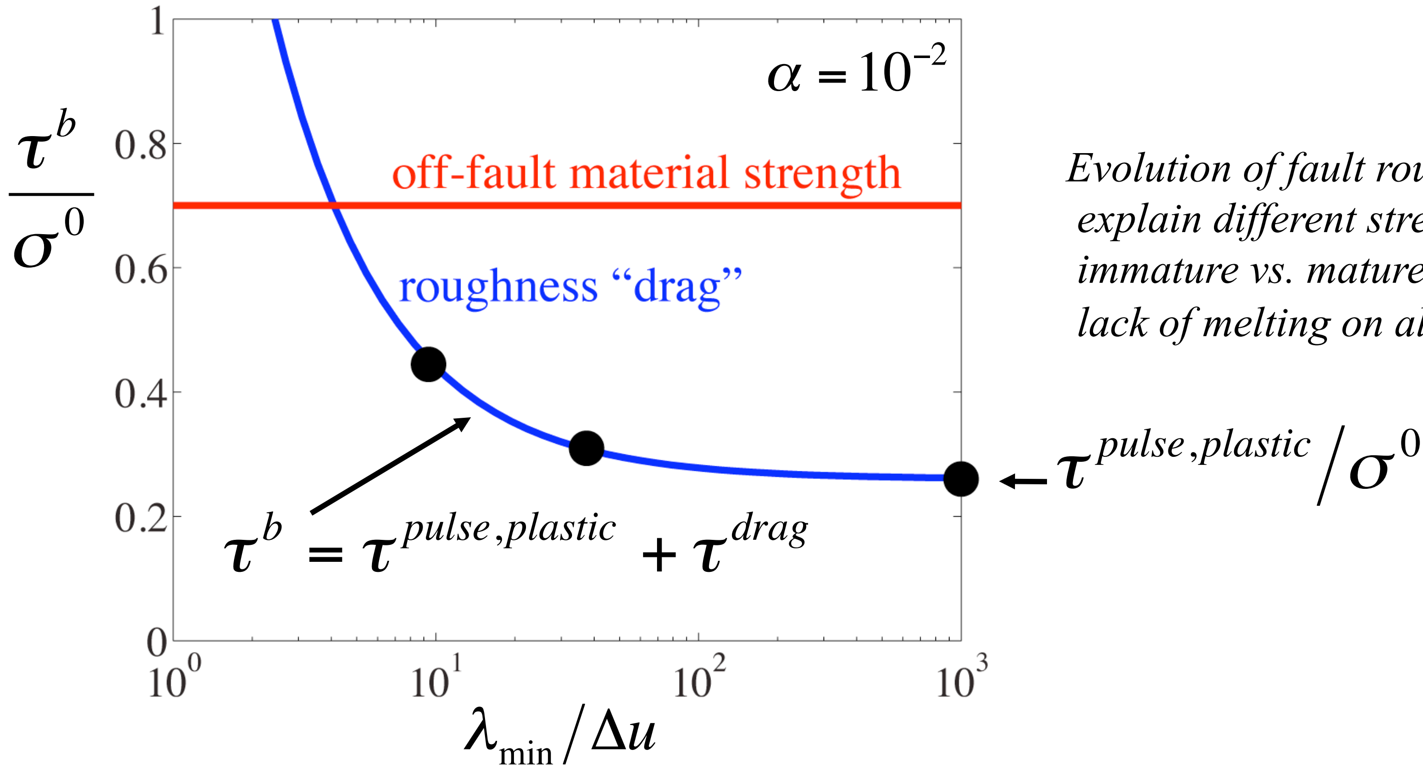
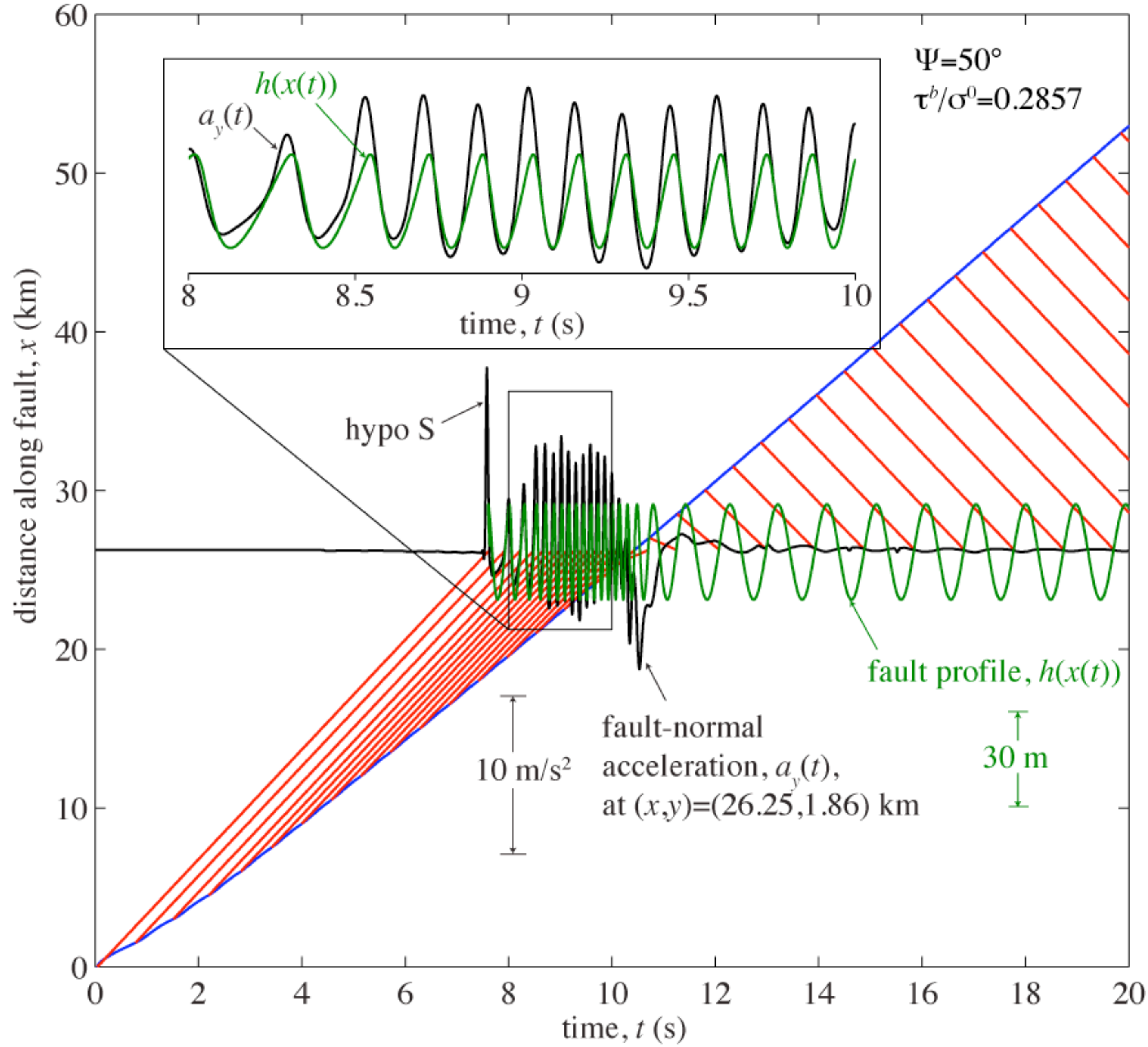
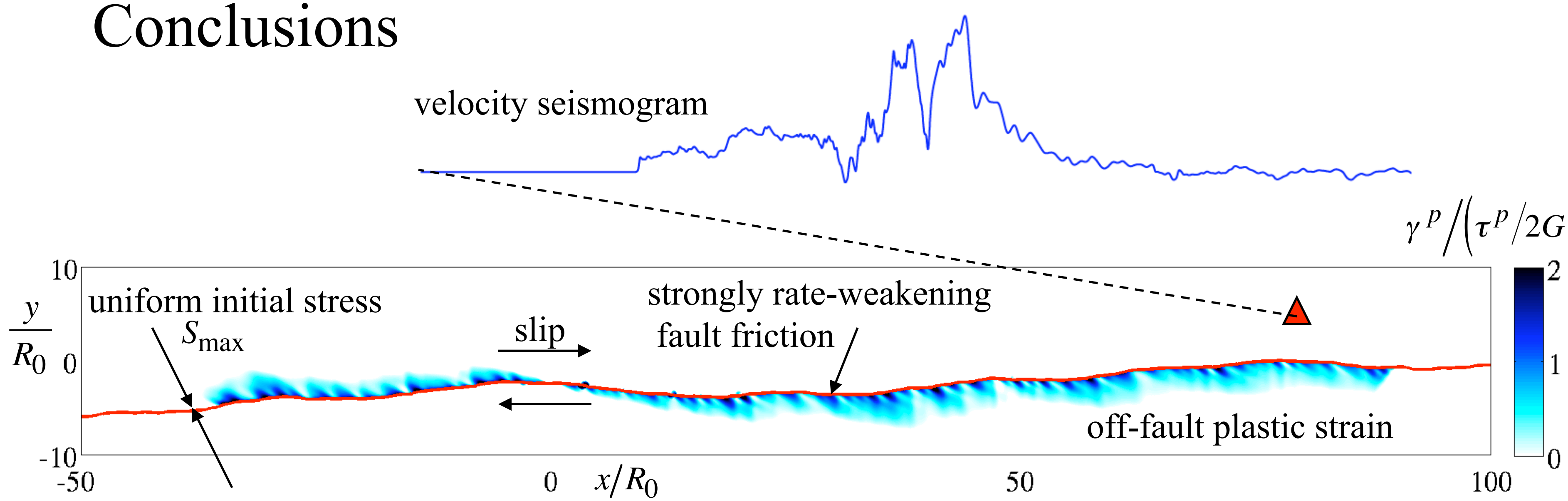


Evolution of fault roughness might explain different stress levels on immature vs. mature faults (and lack of melting on all faults)

Doppler Effects and Nonstationarity in Near Field



Conclusions



Nonplanar geometry quite important for earthquake dynamics

- Stress perturbations cause inelastic off-fault response (aftershocks, damage zones)
- Roughness influences critical background stress level

New, physics-based approach to generating synthetic broadband ground motion

- Consistency of predicted and observed high frequency ground motion with roughness constrained by direct measurements of fault surface topography
- Single method for both low and high frequencies (*f*-dependent directivity)
- Additional incoherence in 3D requires study