Physical Modeling of Earthquake Rupture Dynamics and Ground Motion

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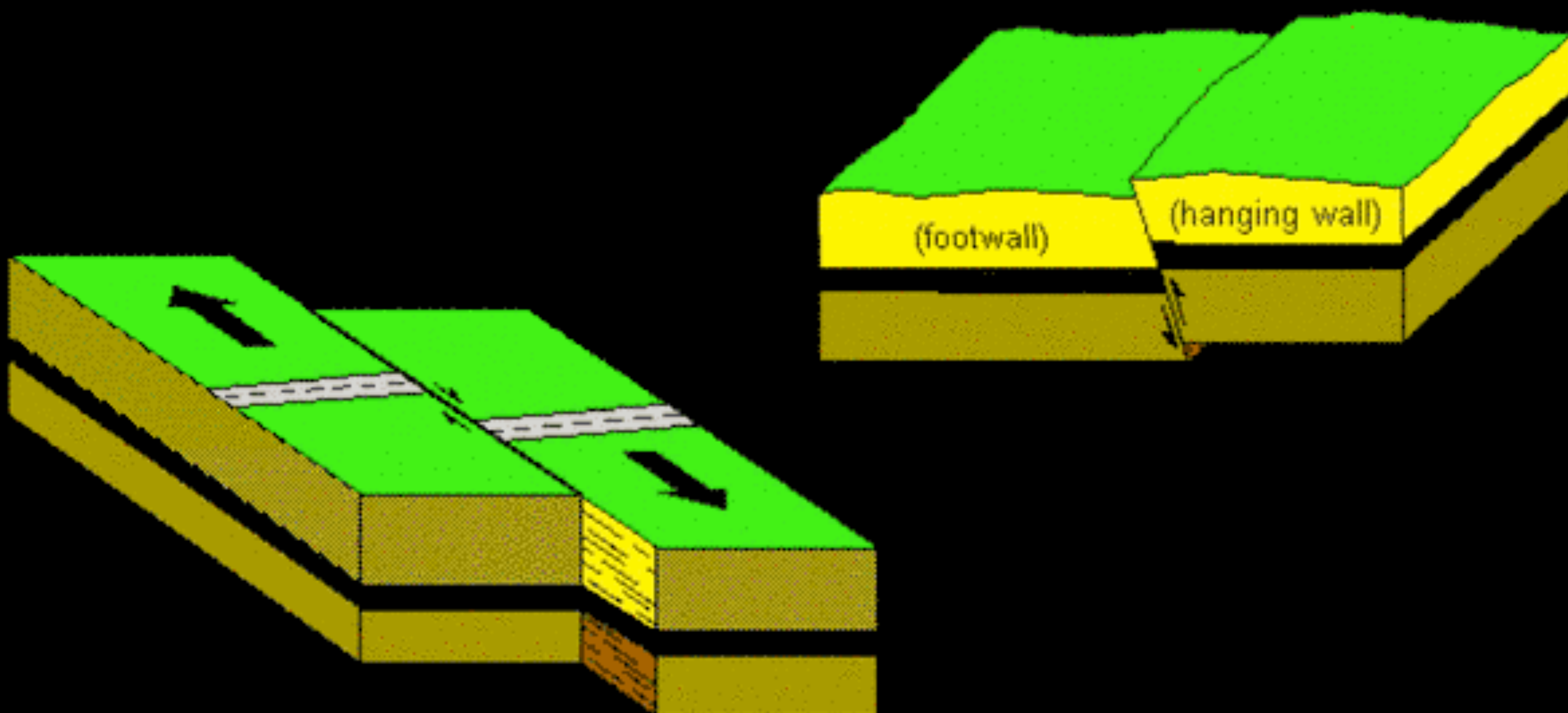
Earthquake: The release of elastic energy by sudden slip on a fault, and the resulting ground shaking and radiated seismic energy by the slip.

August 17, 1999, M_W 7.4 Izmit earthquake, Turkey, > 10,000 deaths

December 26, 2004, M_W 9.2 Sumatra-Andaman earthquake, >200,000 deaths

Fault: A fracture (crack) in the earth, where the two sides move past each other and the relative motion is parallel to the fracture.

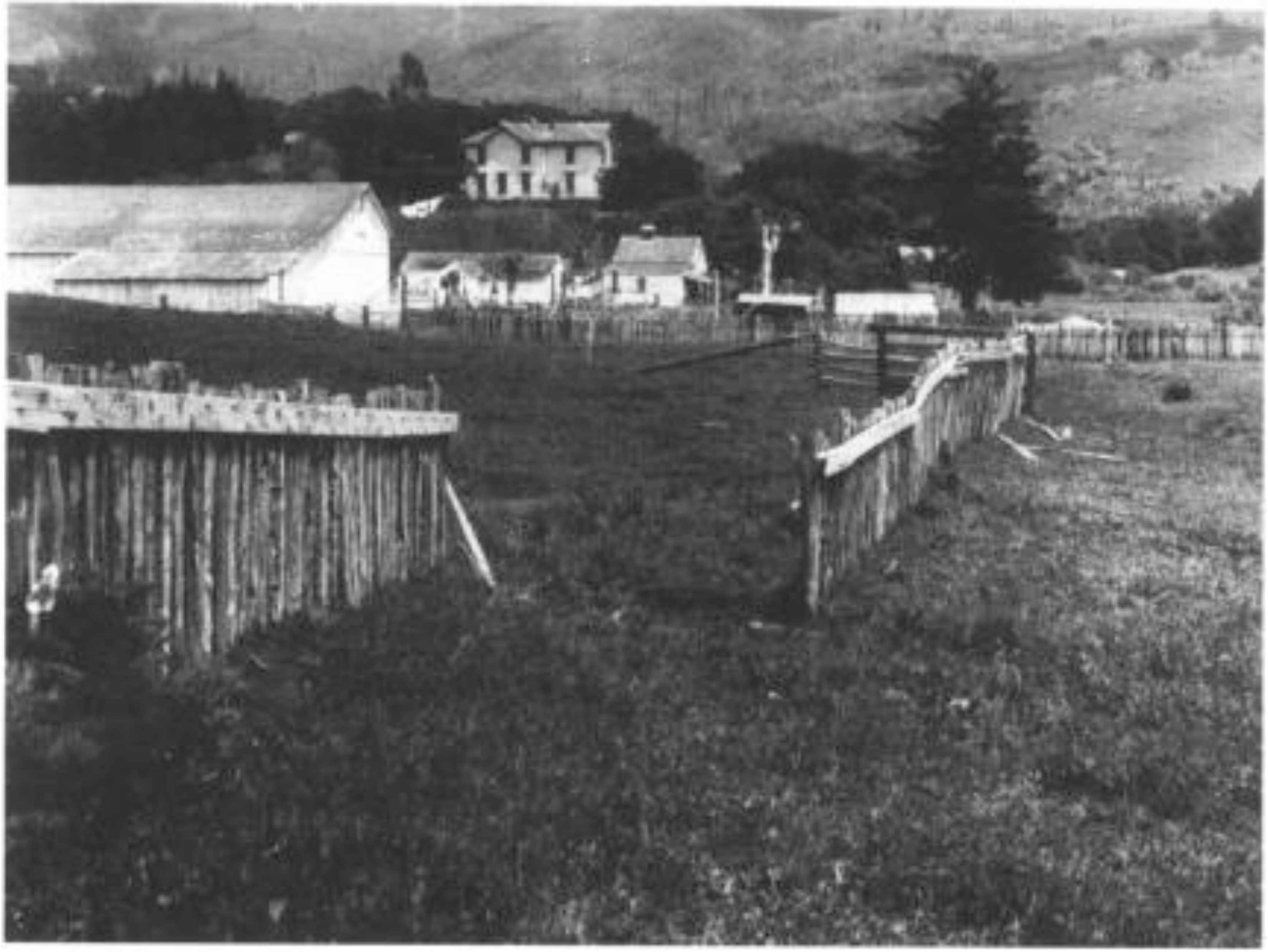


Surface trace (San Andreas Fault, Carrizo Plain)

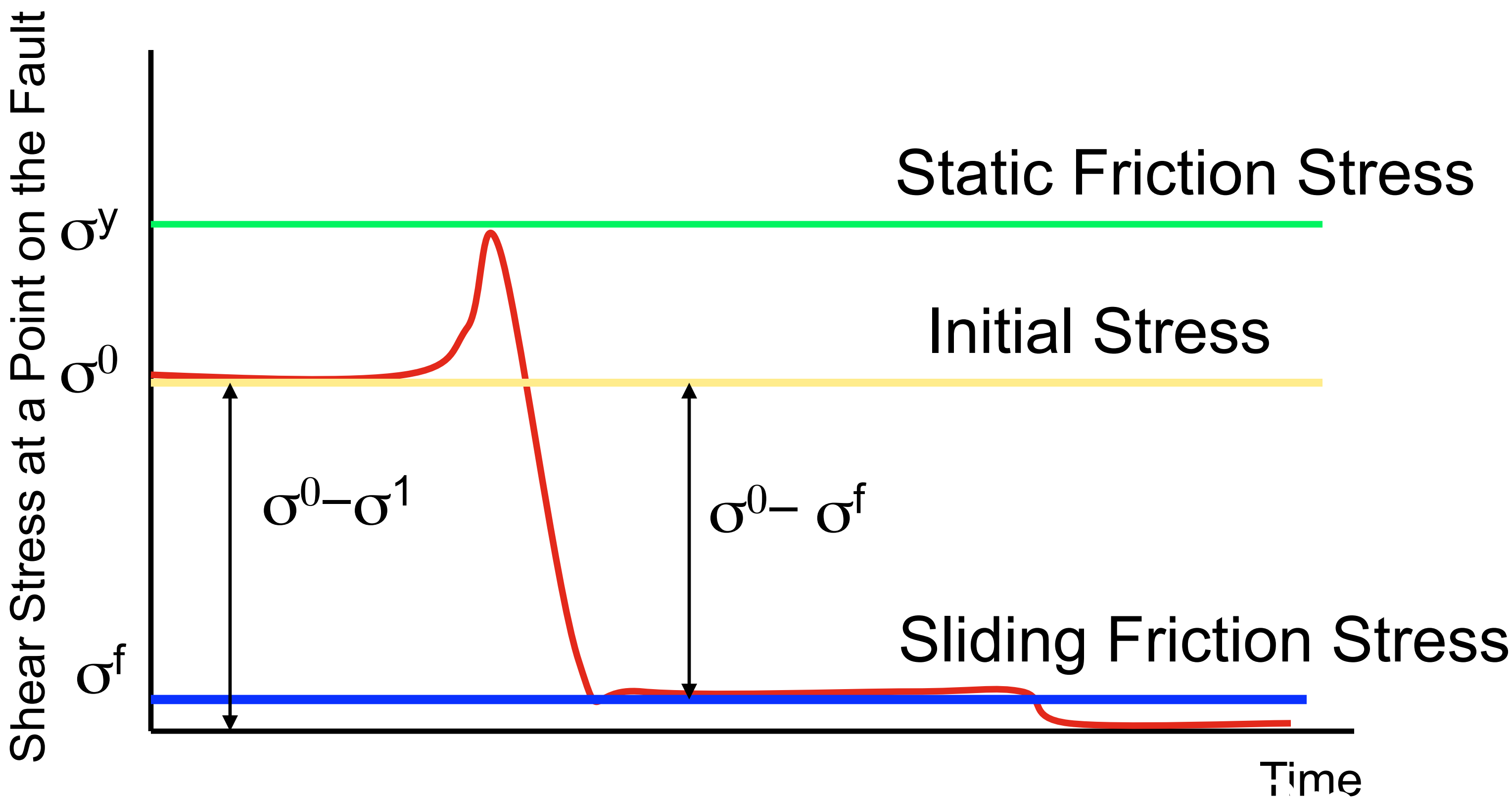
1983 Borah Peak Earthquake, Idaho

Strike-Slip Faulting 1979 Imperial Valley Earthquake

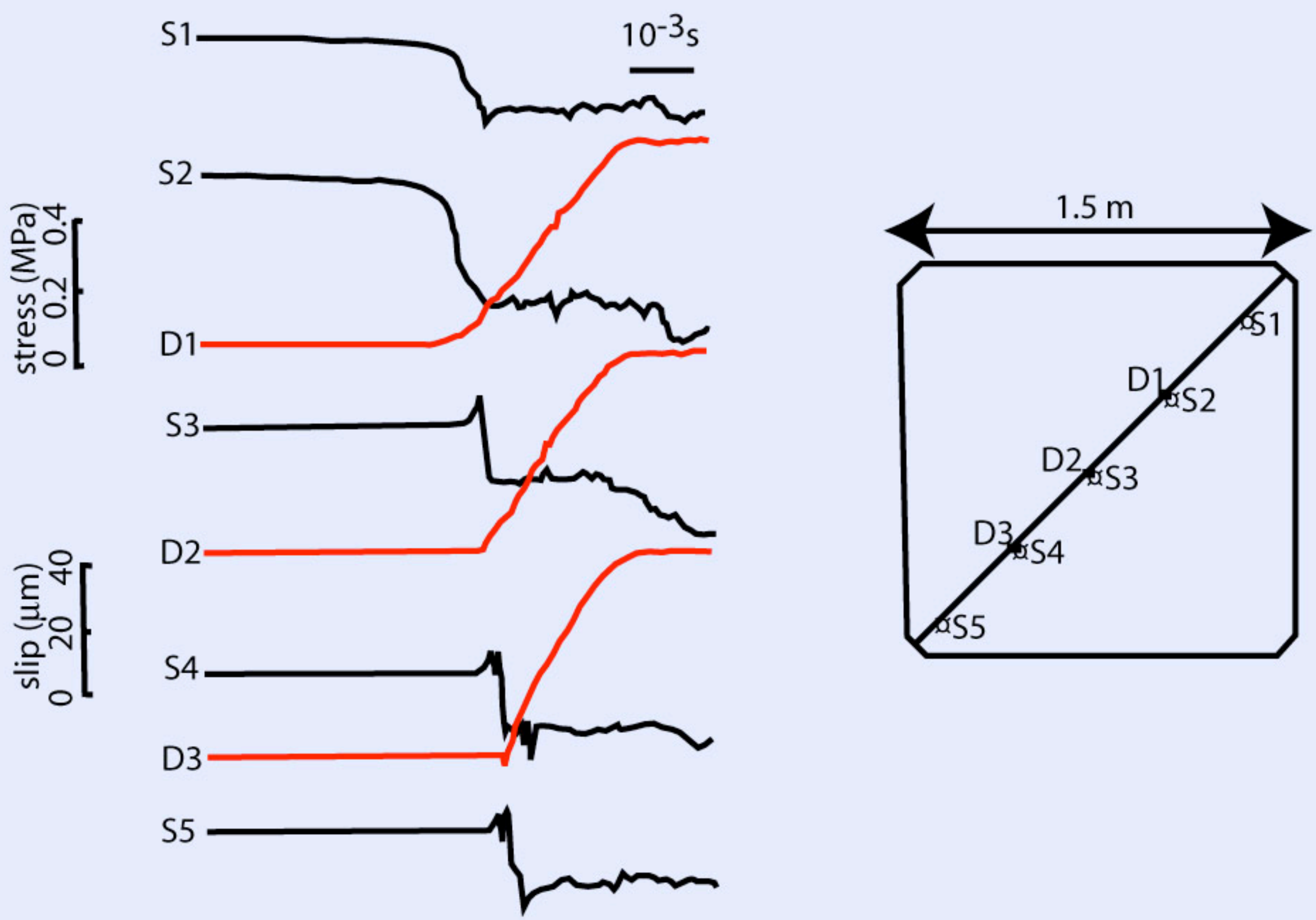
Elastic Rebound Theory



Behavior of Shear Stress at a Point on the Fault



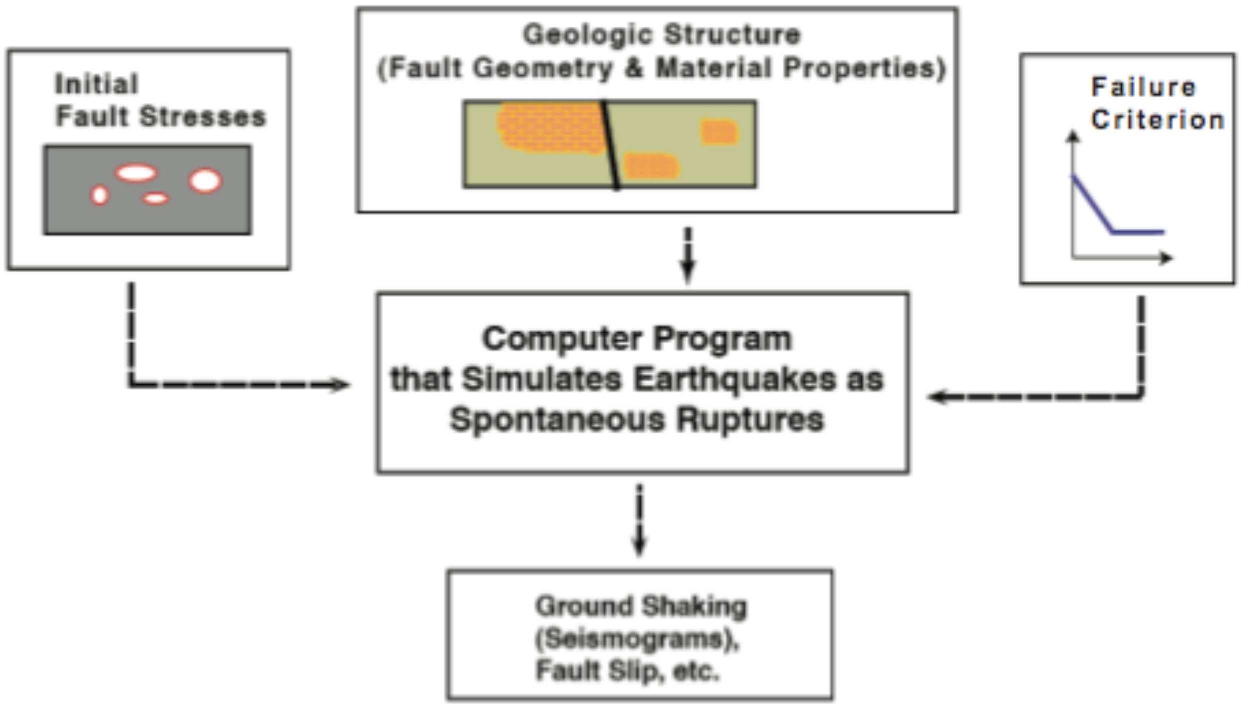
Dieterich's Experiments



S1–S5 give shear stress parallel to the fault. D1–D3 give slip on fault.

Modified from Dieterich (GRL, 1981):

Formulating Dynamic Rupture Model



Harris et al. (2009)

Theory of Continuum Mechanics

$$\rho \ddot{u}_i = \sigma_{ij,j} + f_i$$

ρ : *density*

u : *displacement*

σ : *stress*

f : *body force*

The equation of motion fully describes the seismic wave propagation.

strain → $\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$ Infinitesimal deformation

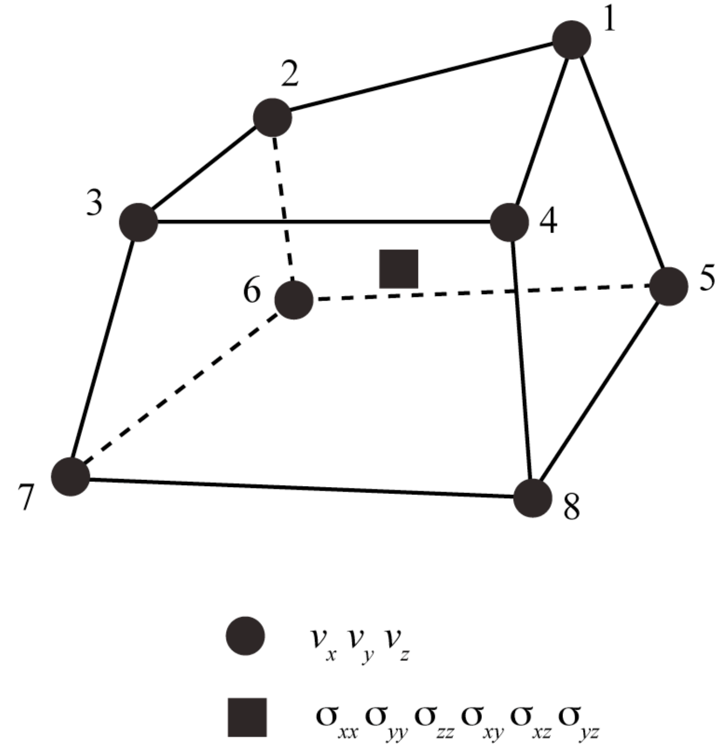
stress → $\sigma_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2\mu \varepsilon_{ij}$ Isotropic, elastic material

Explicit Finite Element Method

• Eight-node hexahedral elements

• Diagonal mass matrix

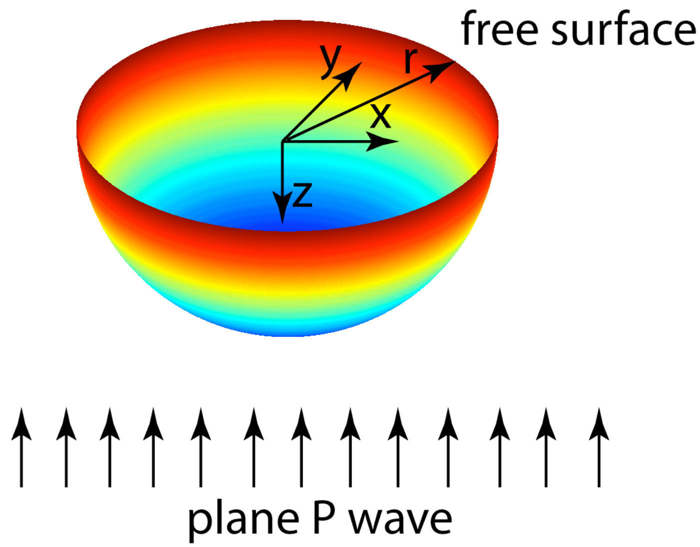
• One-point integration and hourglass control (Goudreau and Hallquist, 1982)



• Efficient for incorporating different material constitutive laws, e.g., nonlinearity.

Ma and Liu, 2006

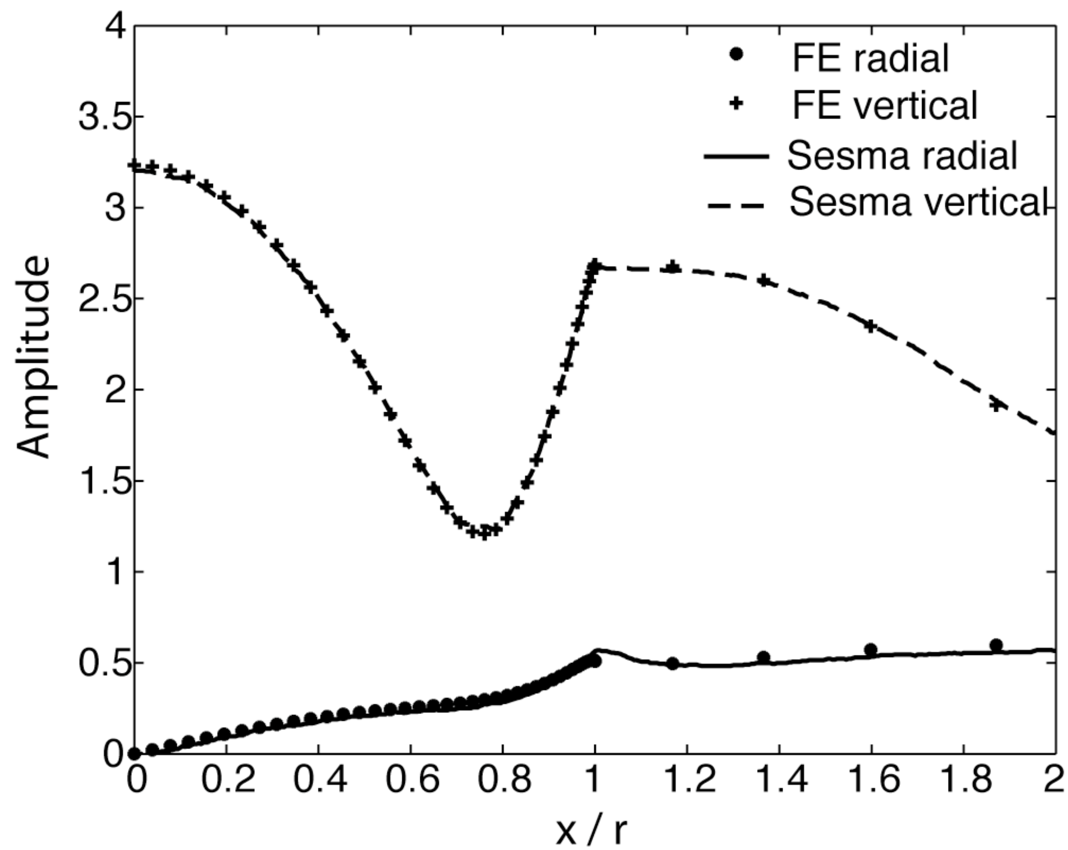
Validation of the FEM



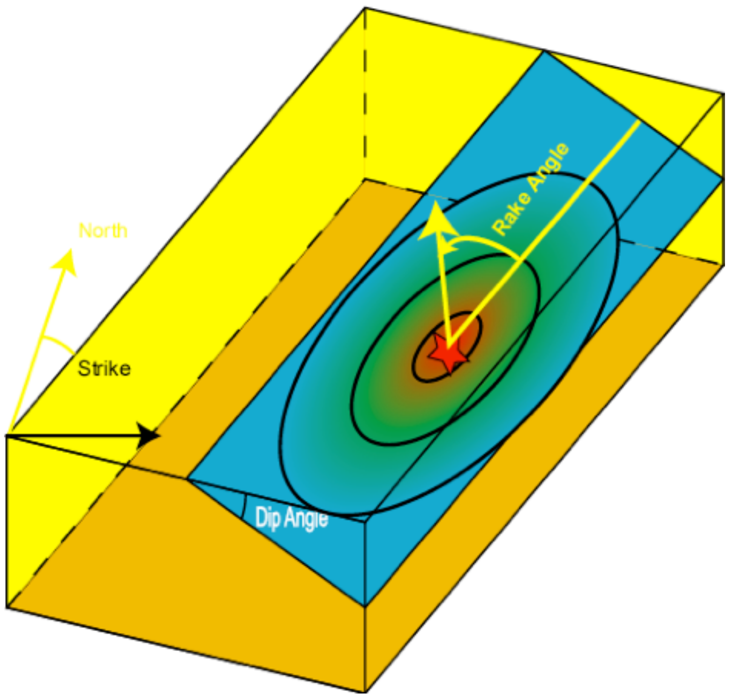
A hemisphere crater on the surface subjected to a vertically incident plane P wave.

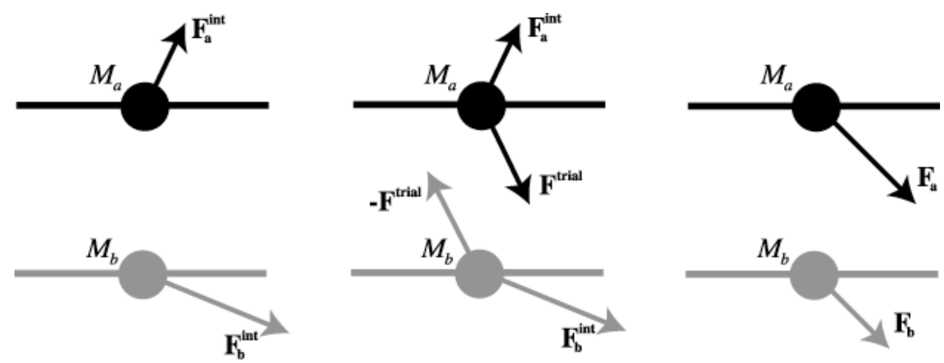
Sanchez-Sesma (1983)

$\lambda = 4r$



Modeling of Fault Boundary Conditions





Traction on fault satisfies the specified friction law.

Andrews (1999)

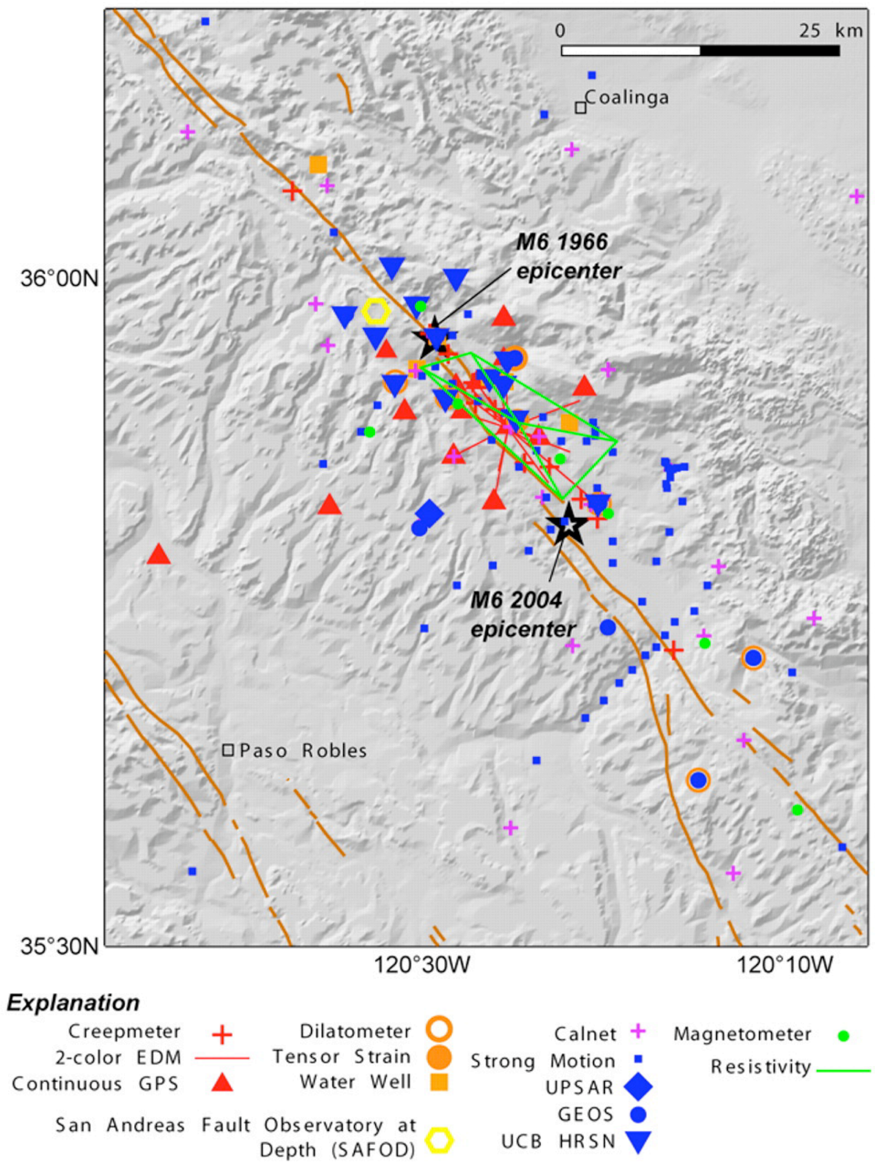
Day et al. (2005)

Ma and Archuleta (2006)

Traction changes between nodes give rise to driving forces to system.

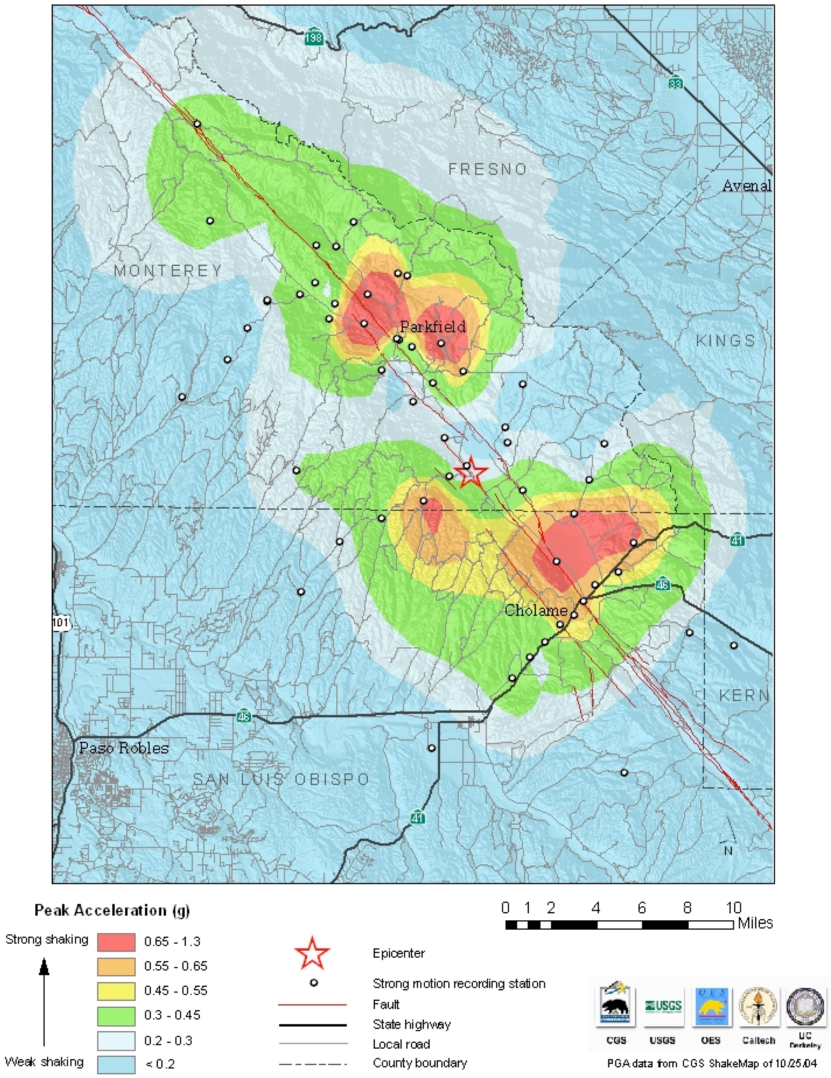
Parkfield Earthquake, M_w 6.0
September 28, 2004

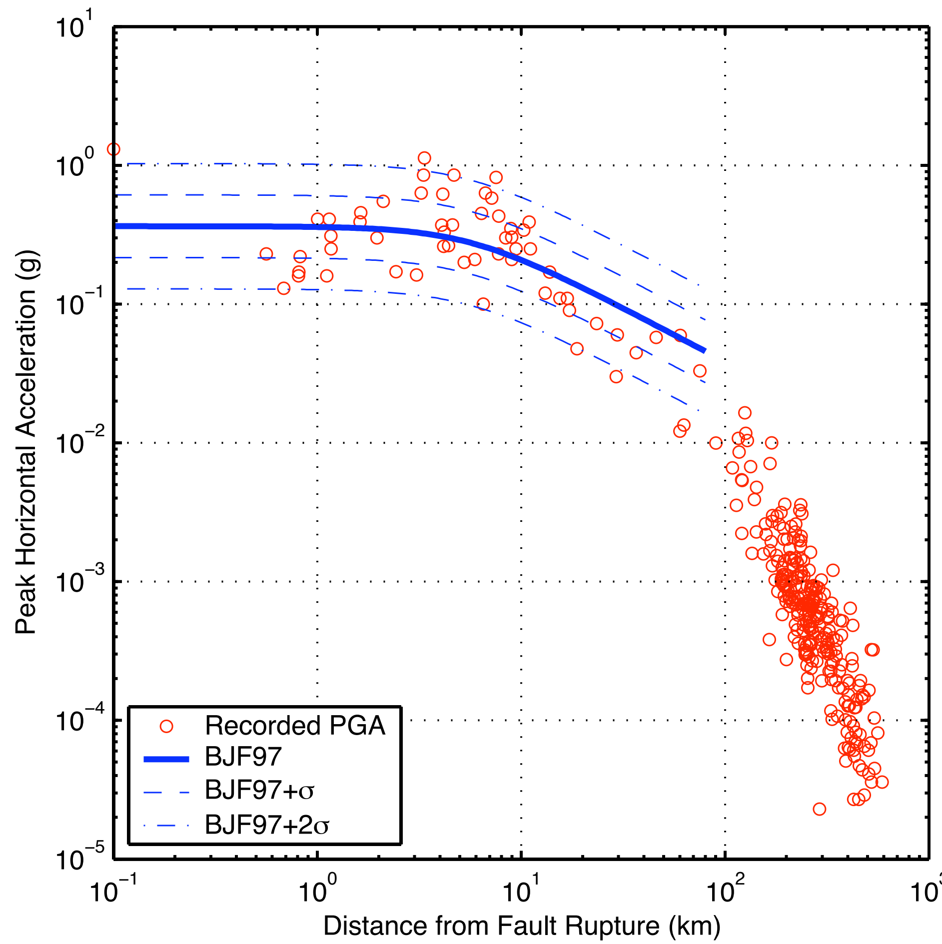
Station Coverage in Parkfield



Harris and Arrowsmith, 2006

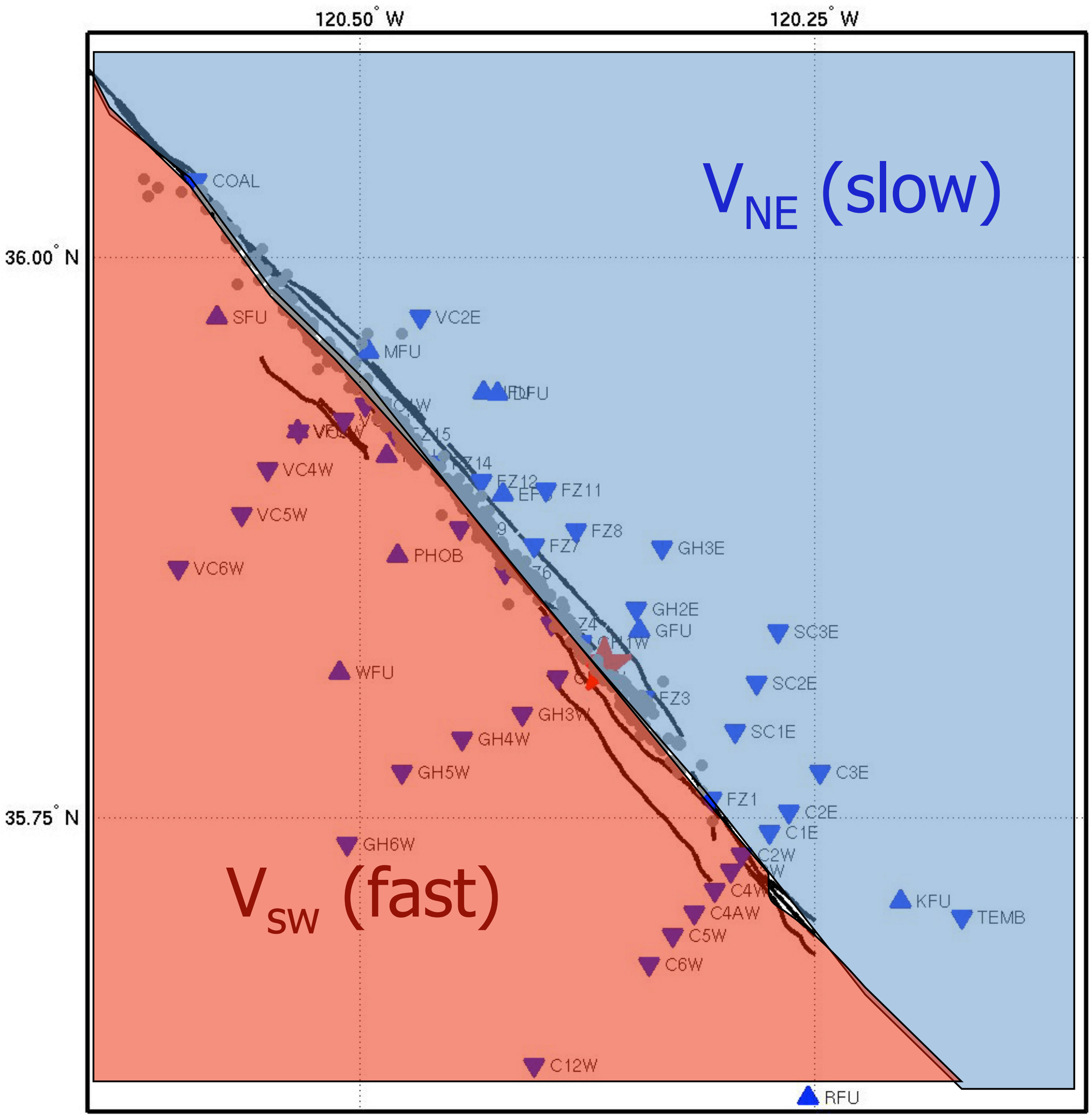
Distribution of Peak Acceleration





Shakal et al, 2004

Velocity Structure

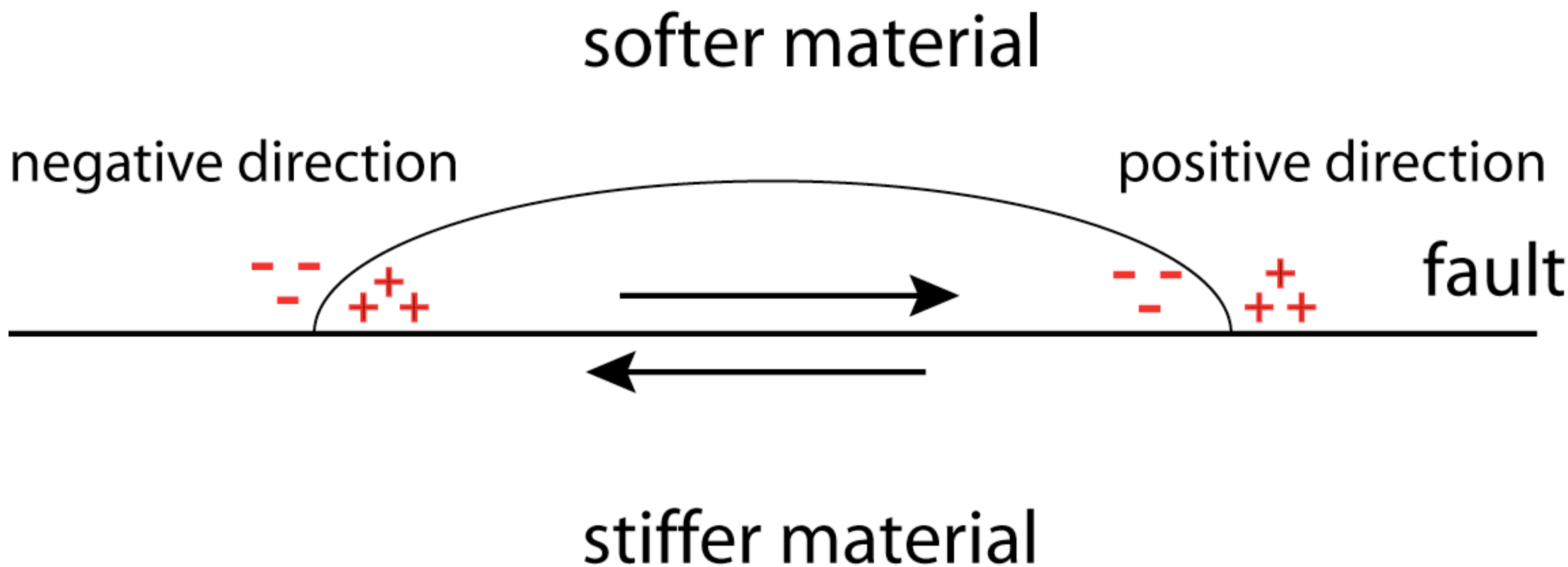


"softer" Franciscan assemblage rocks (NE)

"stiffer" Salinian granitic rocks (SW)

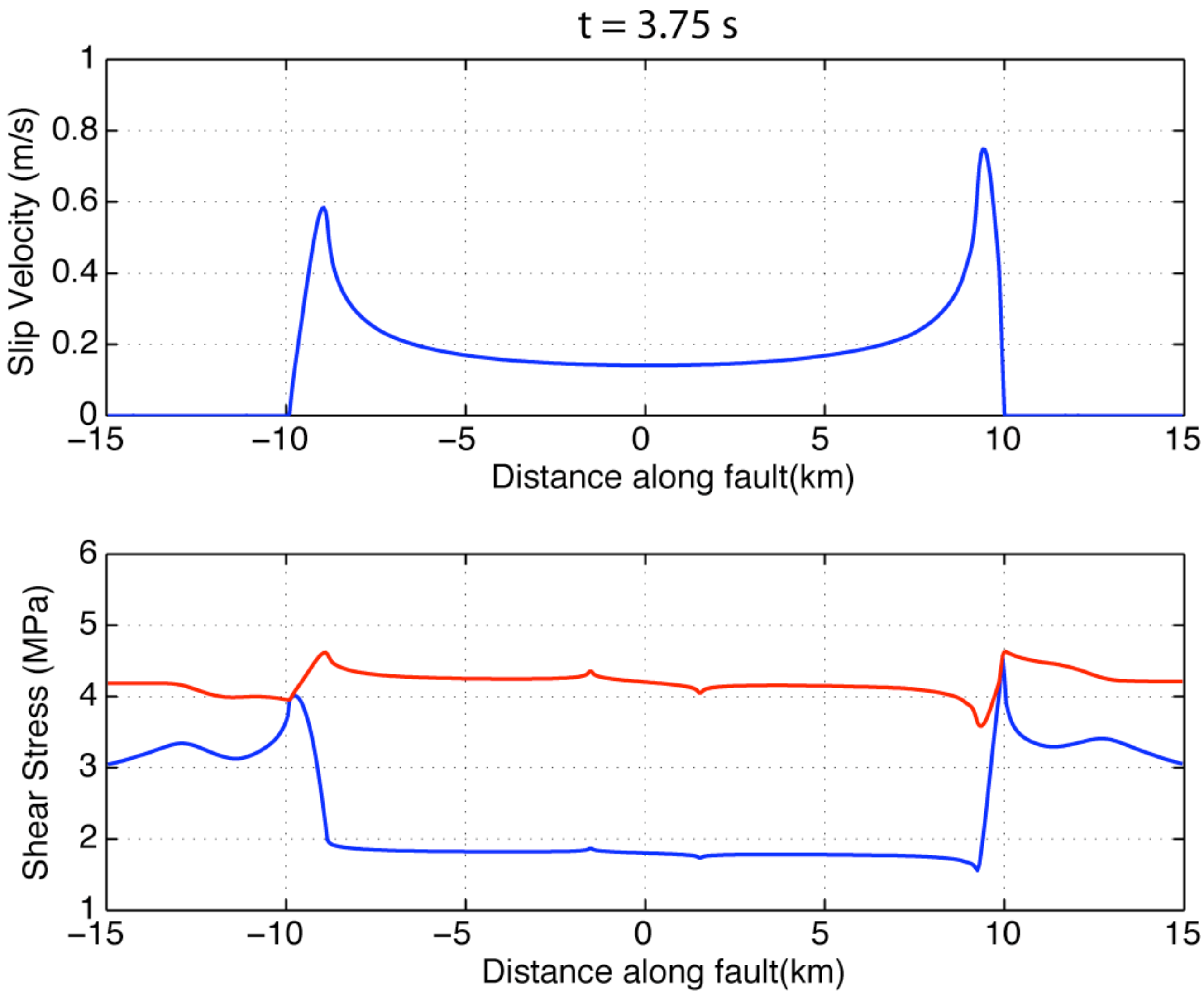
Dynamic Rupture on a Bi-Material Interface

asymmetry in normal stress variations



e.g., Harris and Day (1997, 2005), Rubin and Ampuero (2007) …

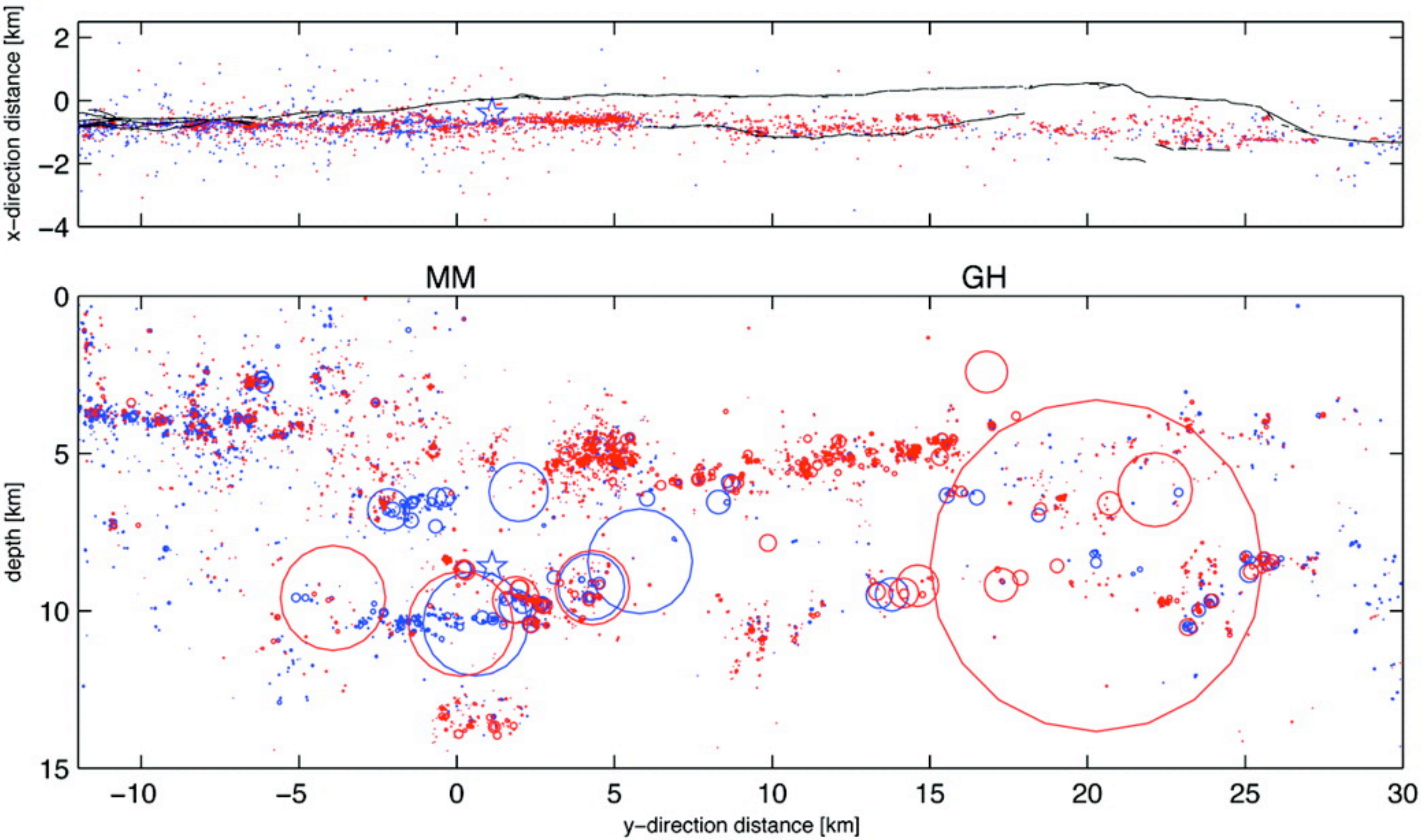
2D Dynamic Rupture Snapshots



e.g., Harris and Day, 1997

20% material contrast

Seismicity 1984-2005

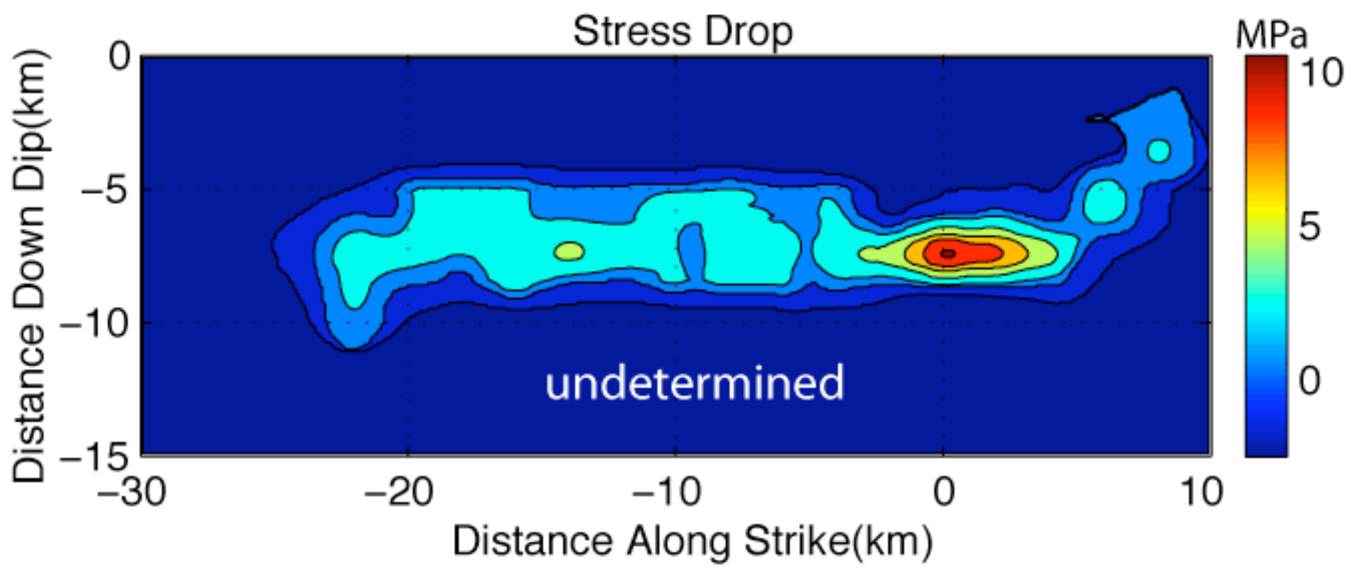


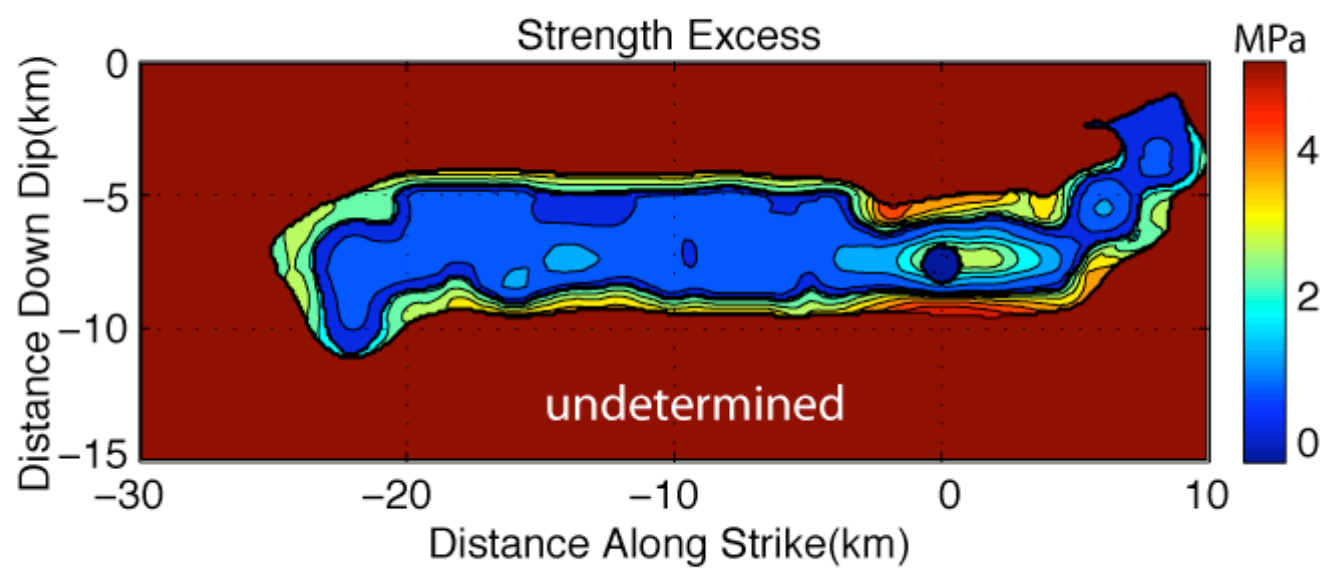
Blue: seismicity before the 2004 mainshock

Red: the 2004 mainshock and its aftershocks

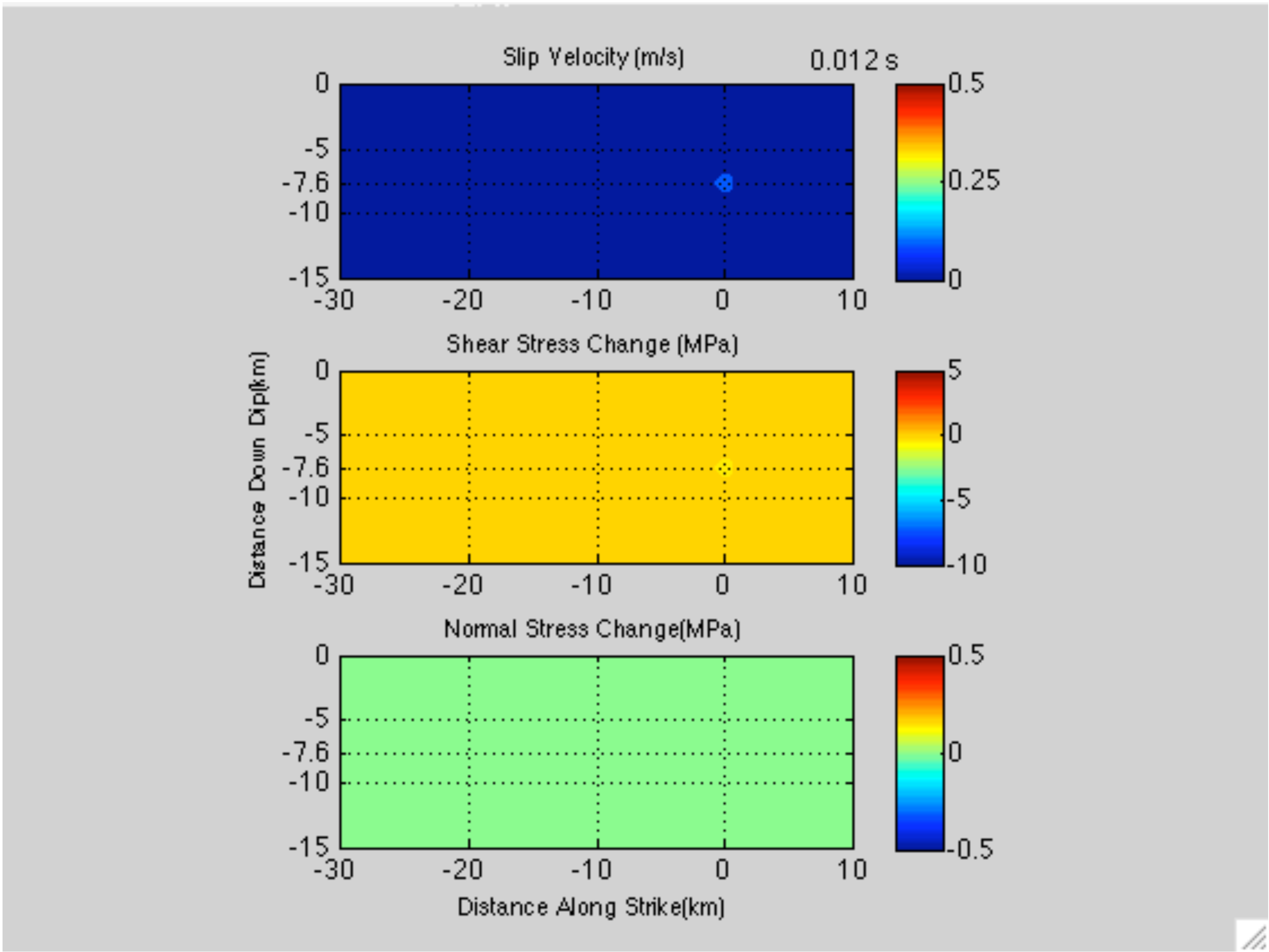
Thurber et al., 2006

Stress Drop and Strength Excess



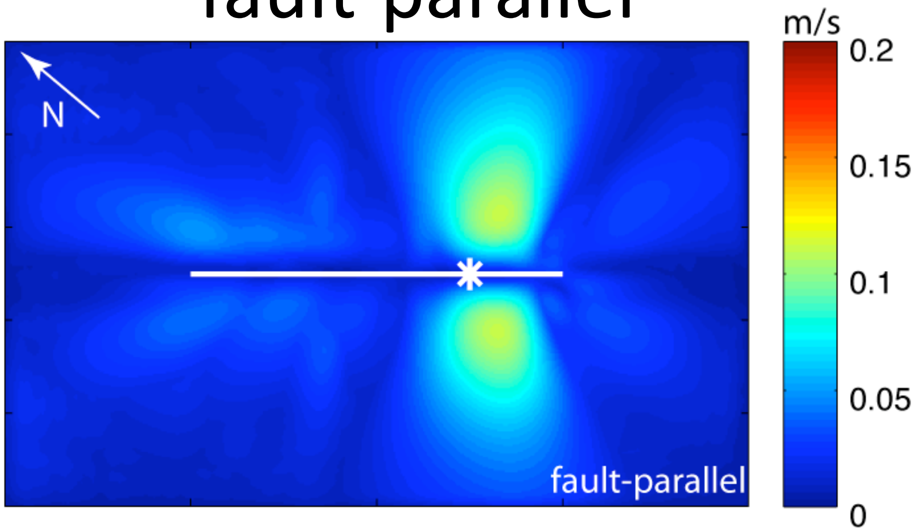


Evolution of Slip Rate, Shear and Normal Stress Changes

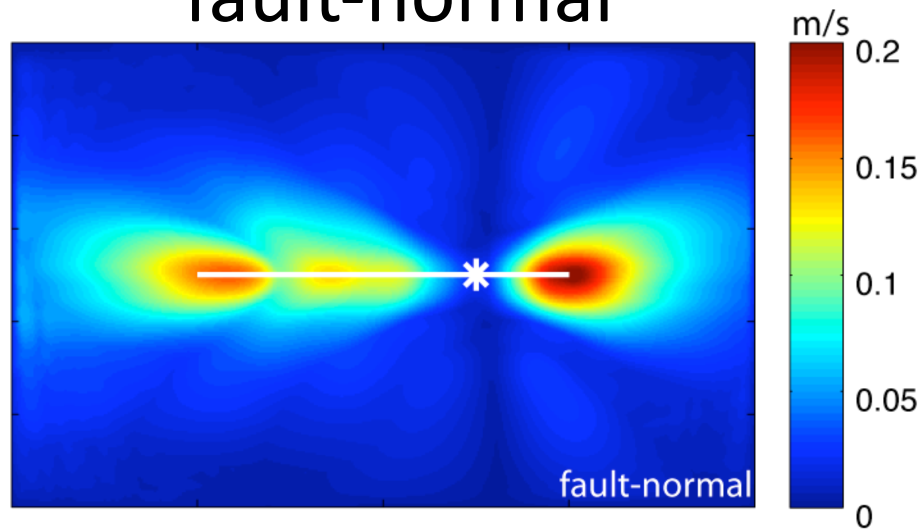


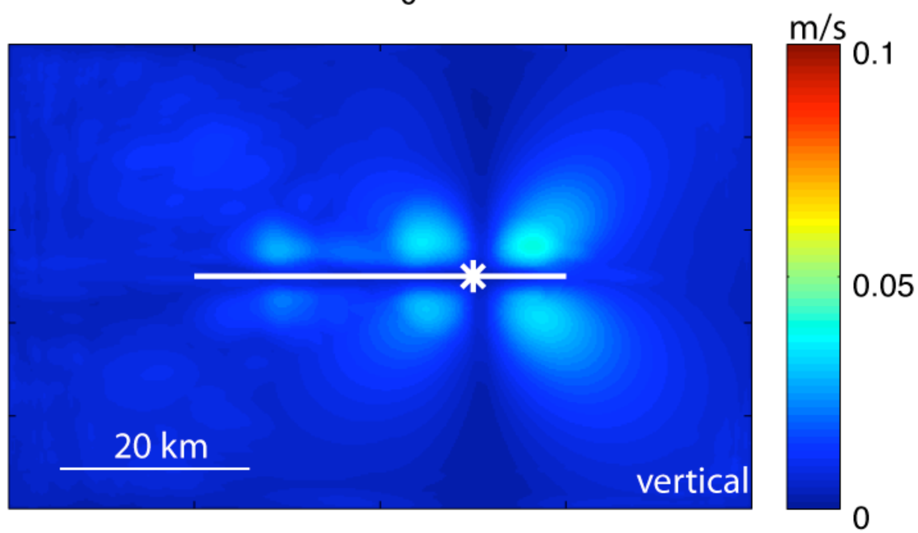
Peak Ground Velocity

fault-parallel



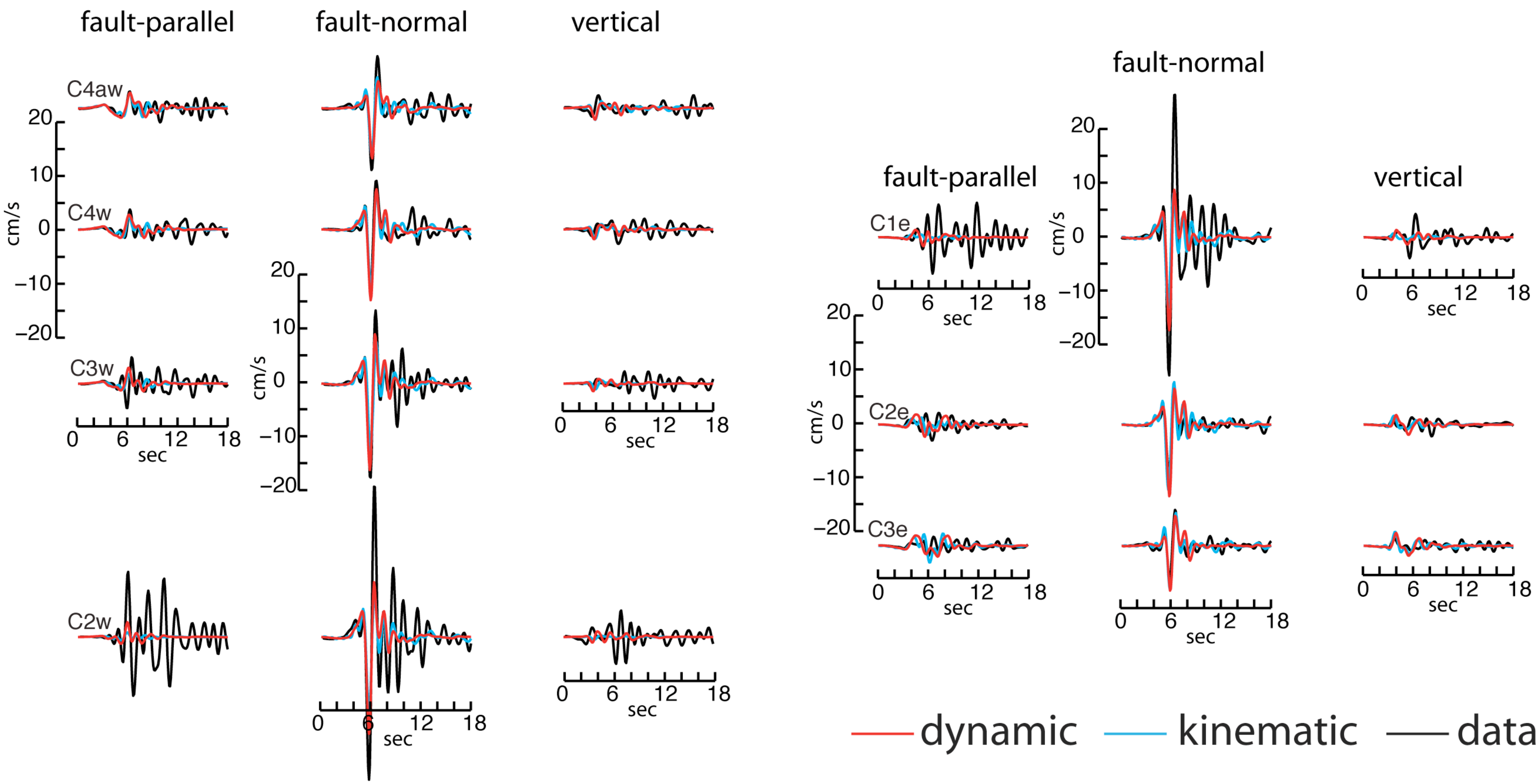
fault-normal





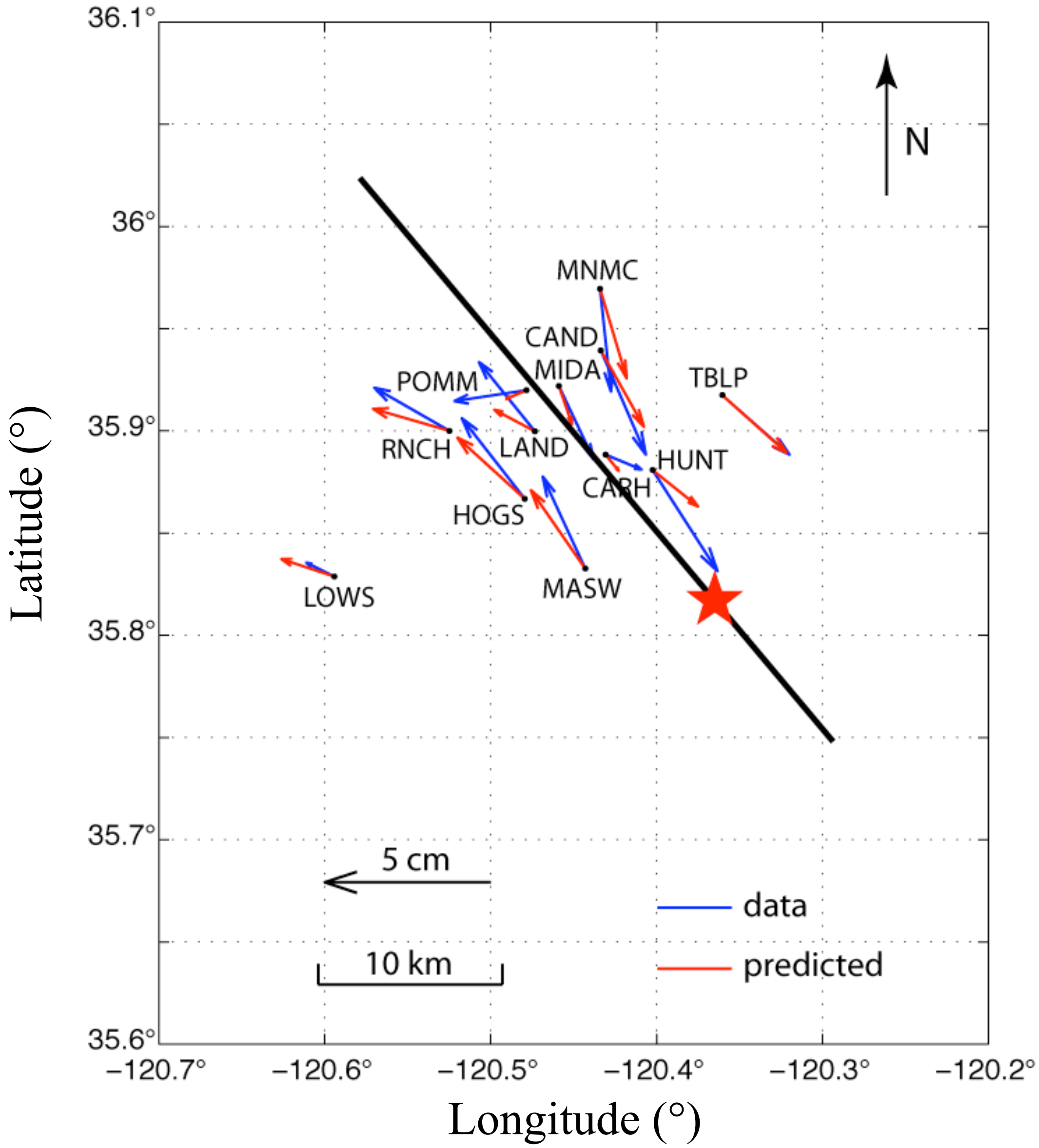
vertical

Synthetics vs. Data

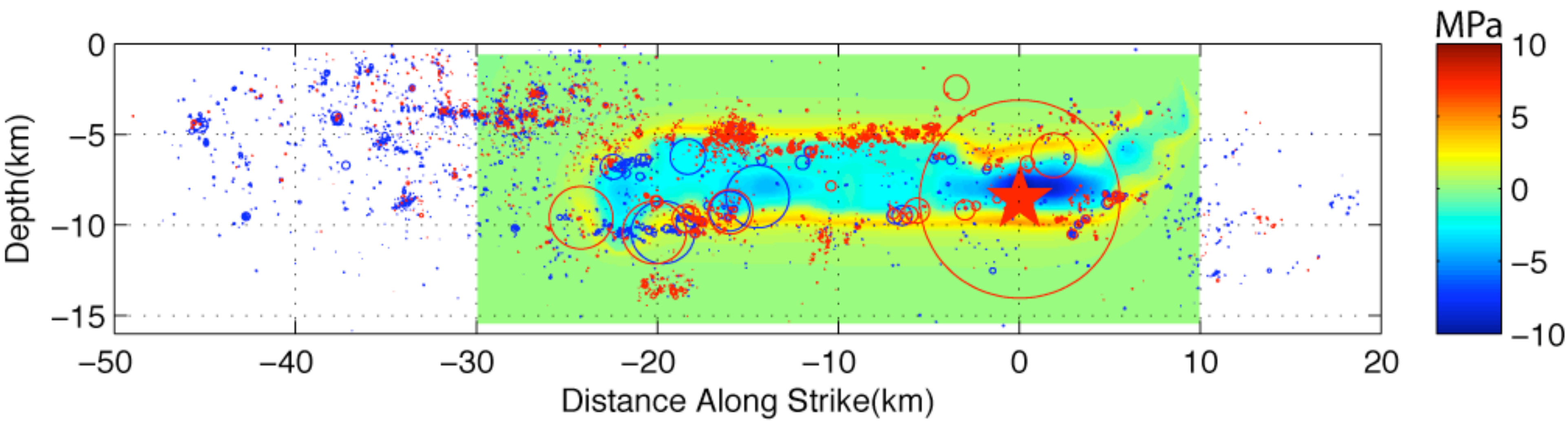


0.16 - 1.0 Hz

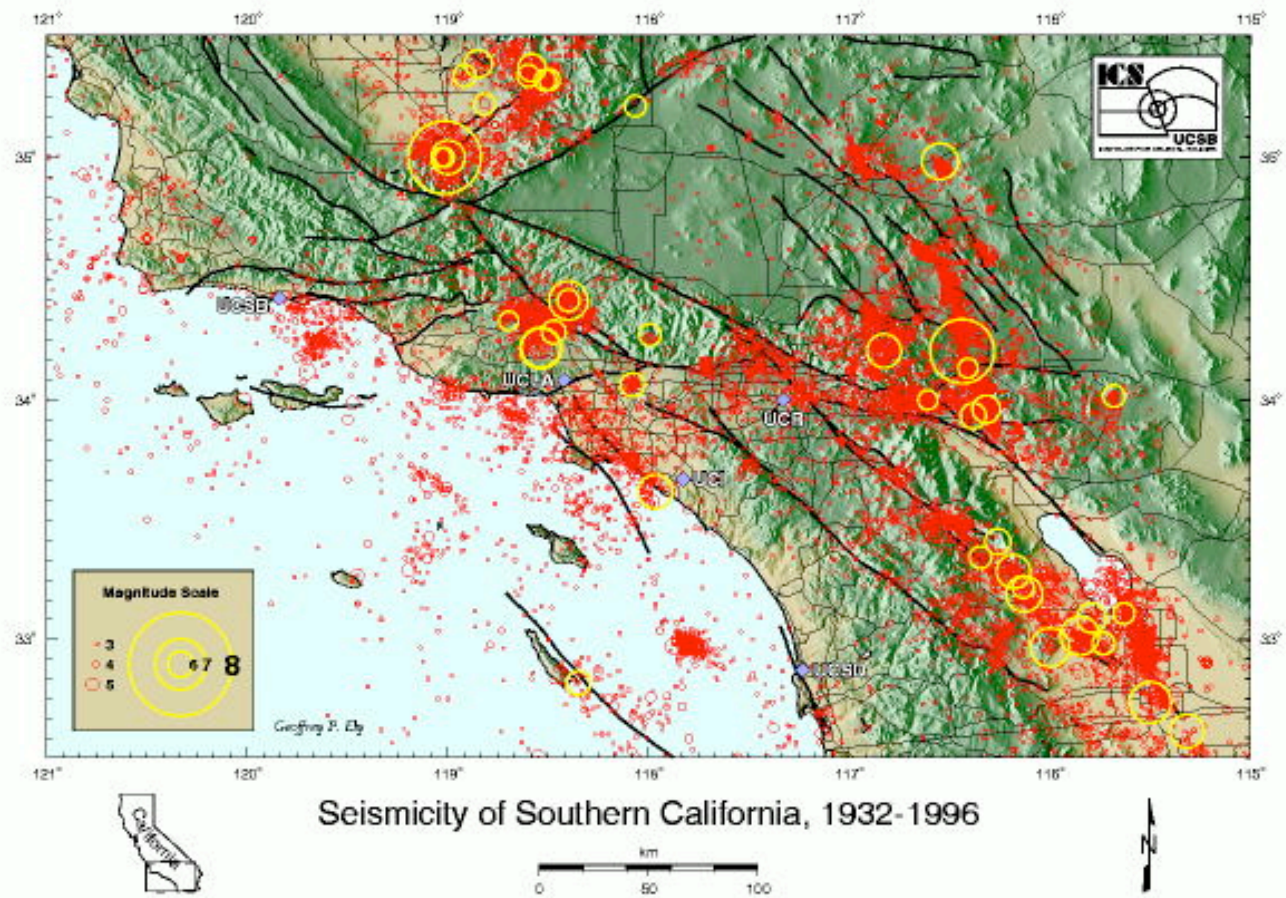
Predicted Coseismic Offset vs. GPS



Coseismic Stress Change vs. Seismicity Before (blue) and After (red) the Mainshock

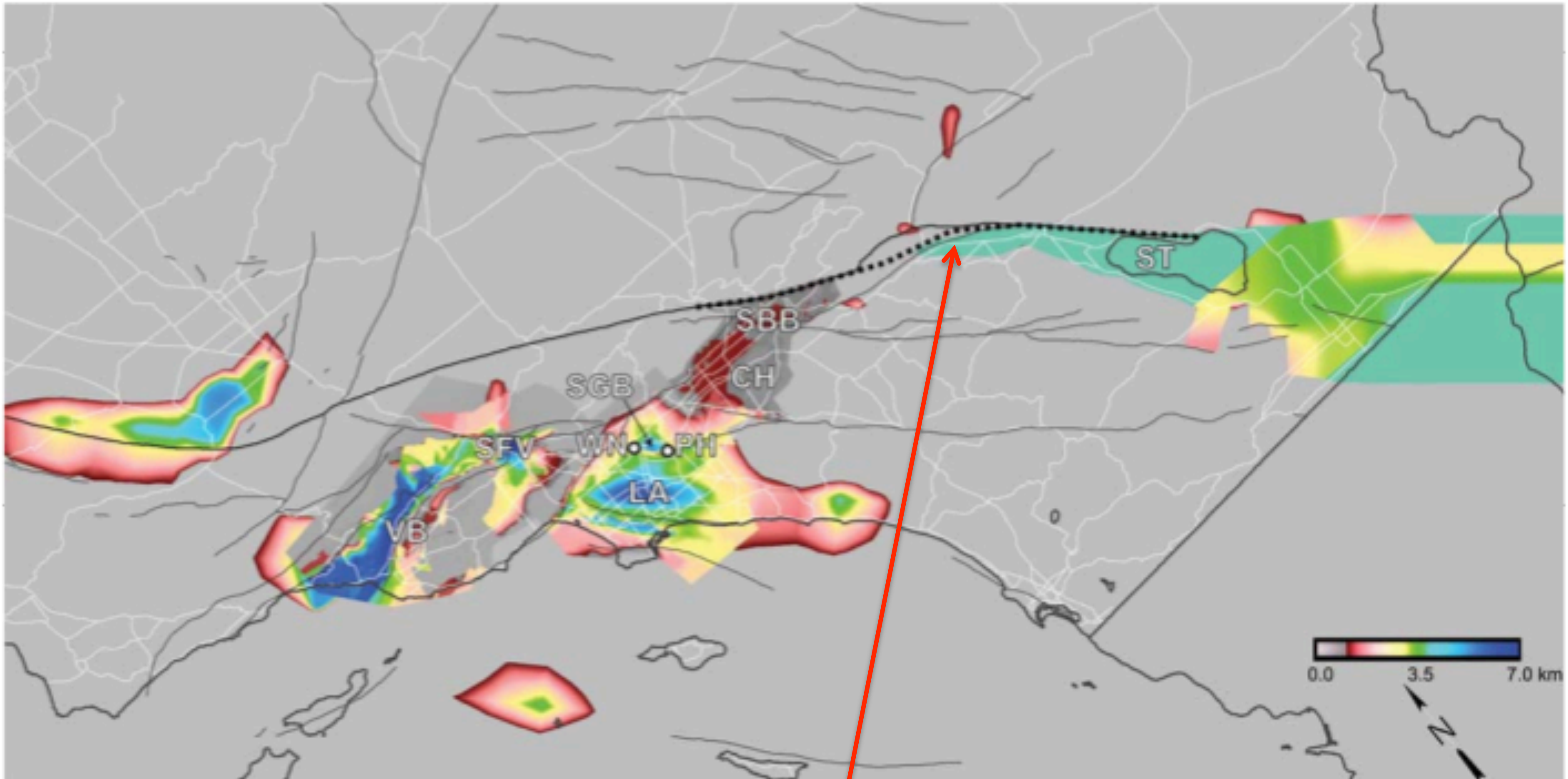


Seismicity of Southern California, 1932 - 1996



Large earthquakes are less frequent and "unpredicted".

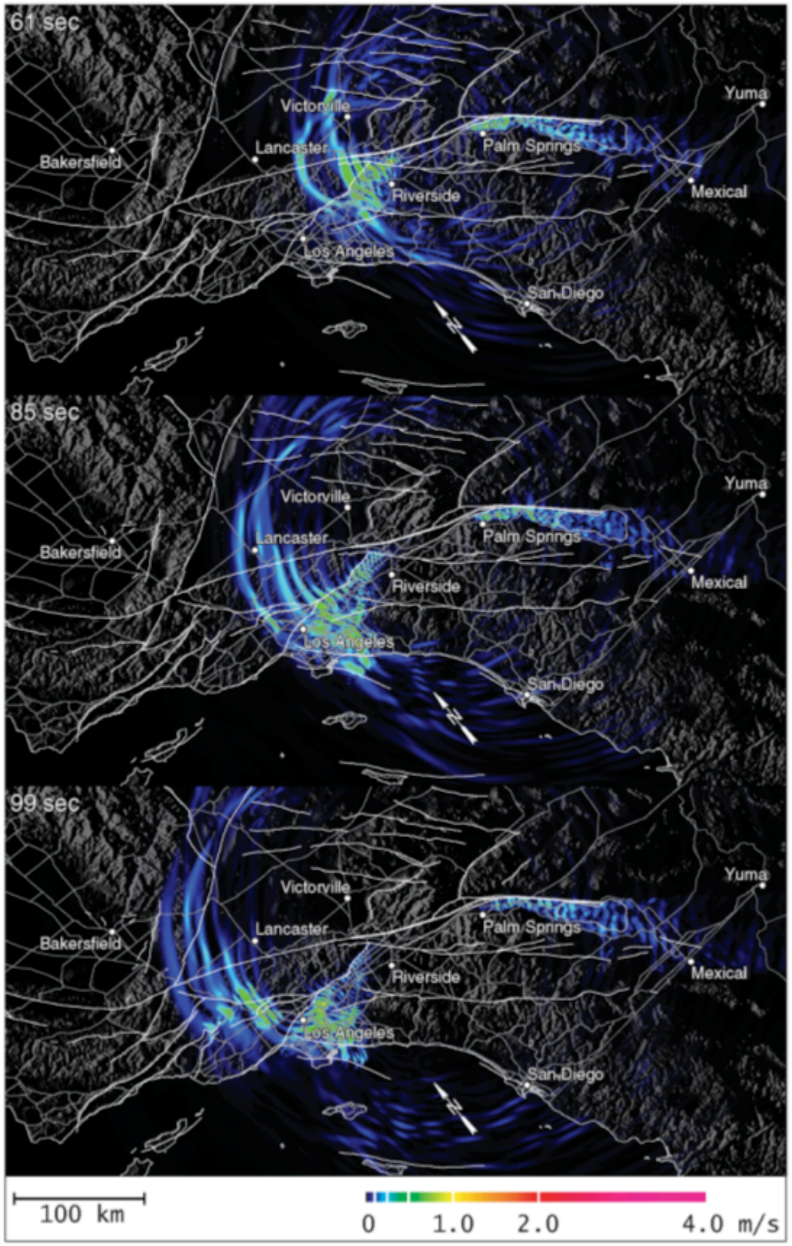
Strong Motion Prediction: Terashake



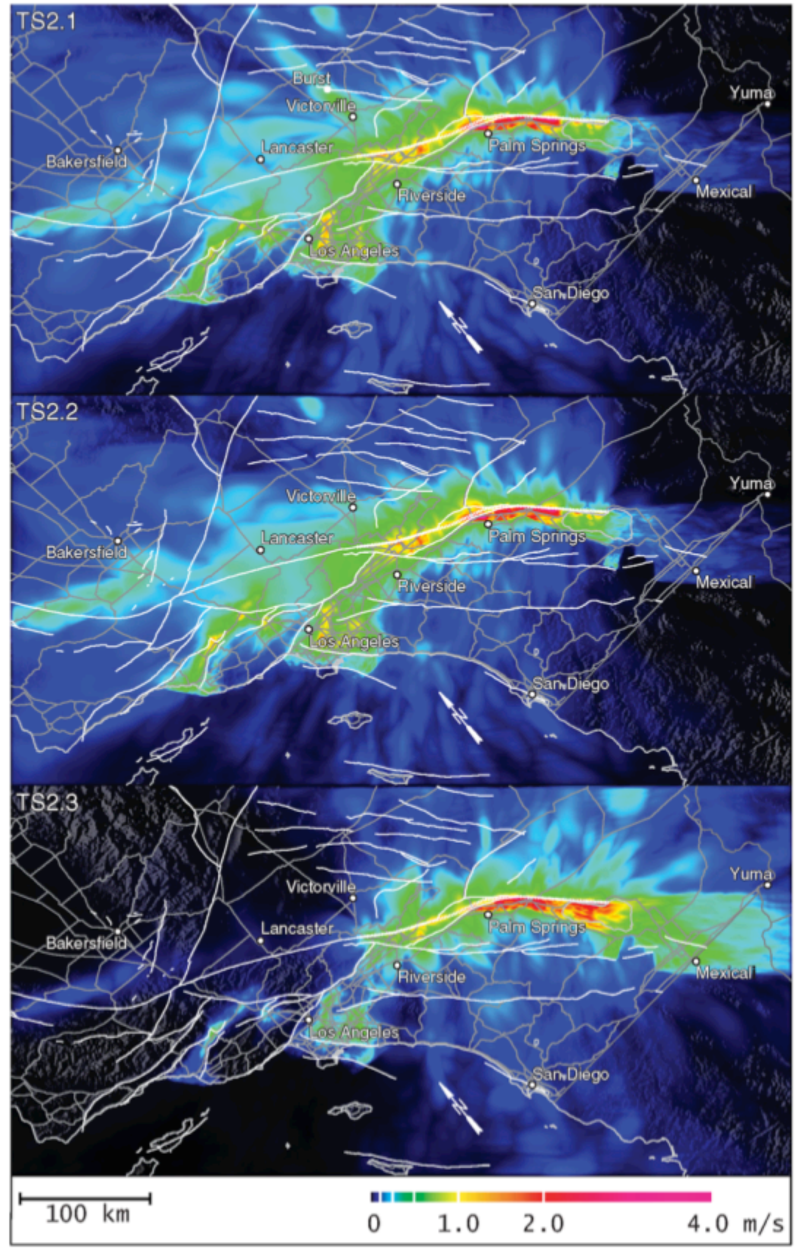
M_W 7.7 Earthquakes on the Southern San Andreas Fault

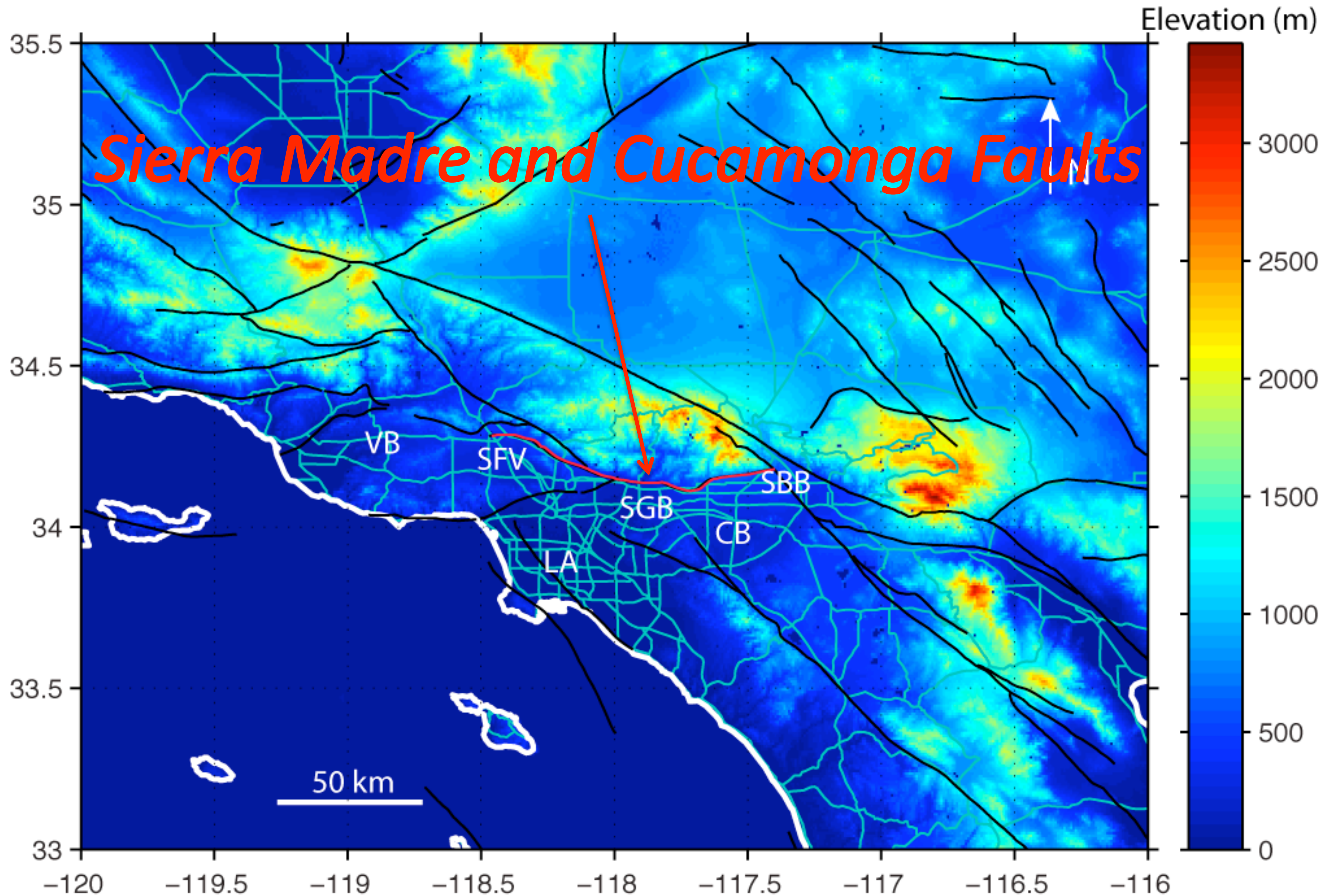
Olsen et al., 2008

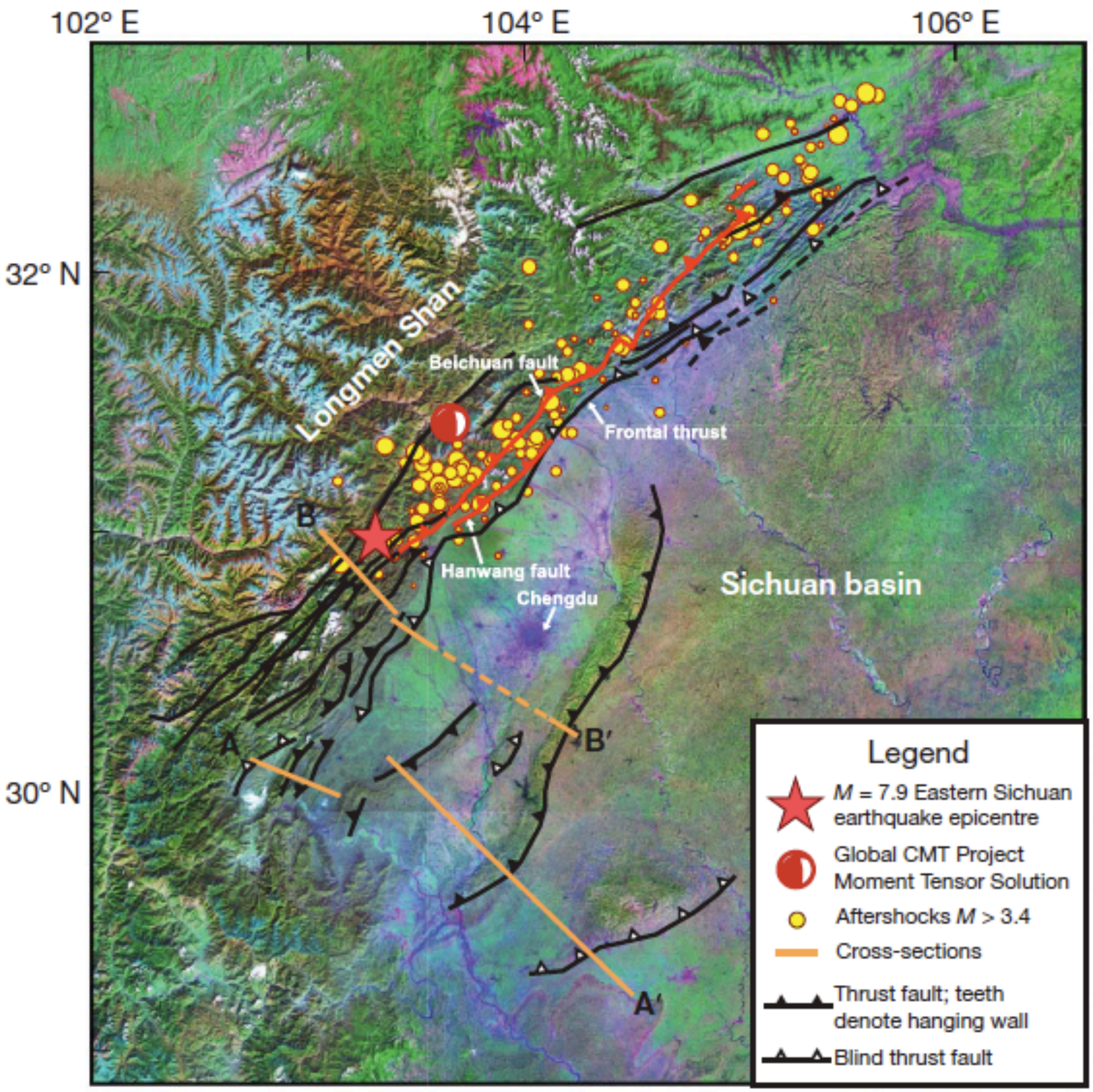
Snapshots of Ground Velocity



Peak Ground Velocity




Sierra Madre and Cucamonga Faults
Elevation (m)
3000
2500
2000
1500
1000
500
0
35.5
35
34.5
34
33.5
33
−120
−119.5
−119
−118.5
−118
−117.5
−117
−116.5
−116
VB
SFV
SGB
SBB
CB
LA
N
50 km

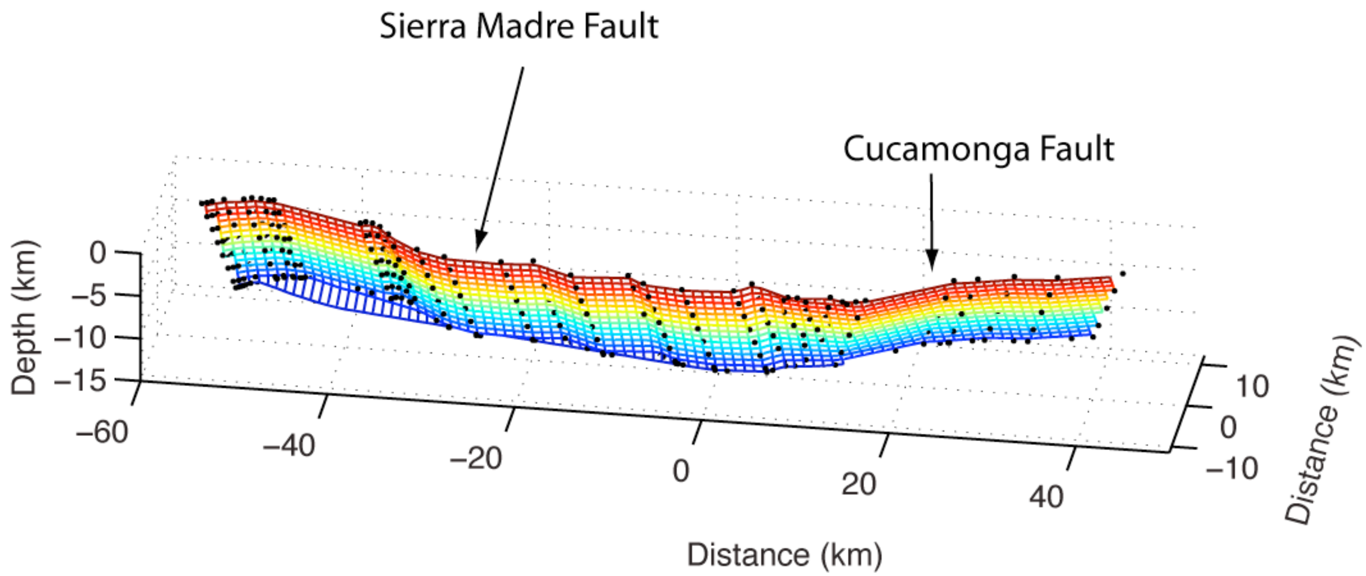


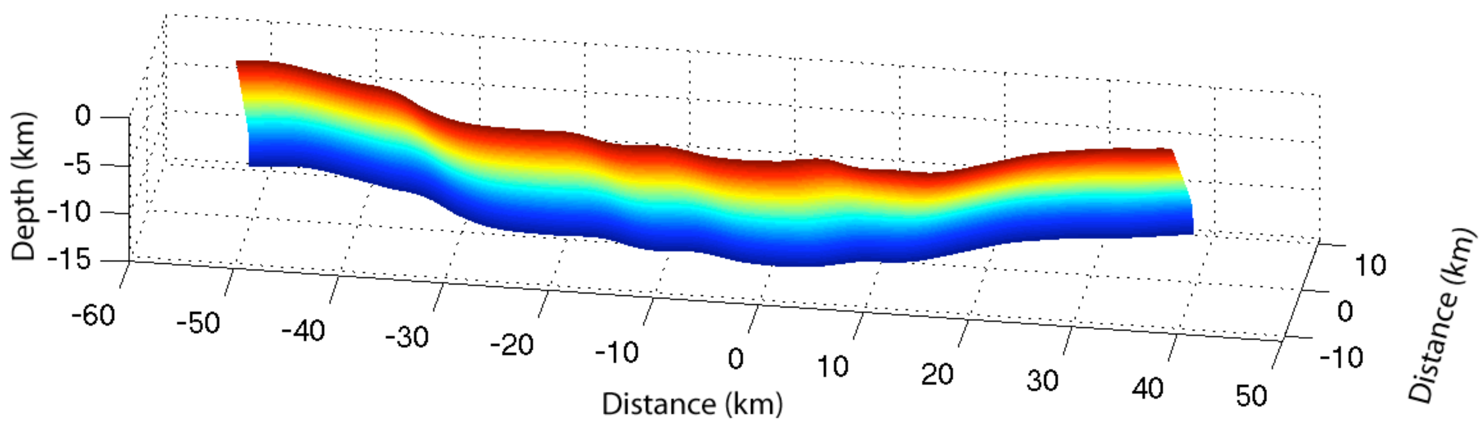
M_W 7.9 Wenchuan Earthquake

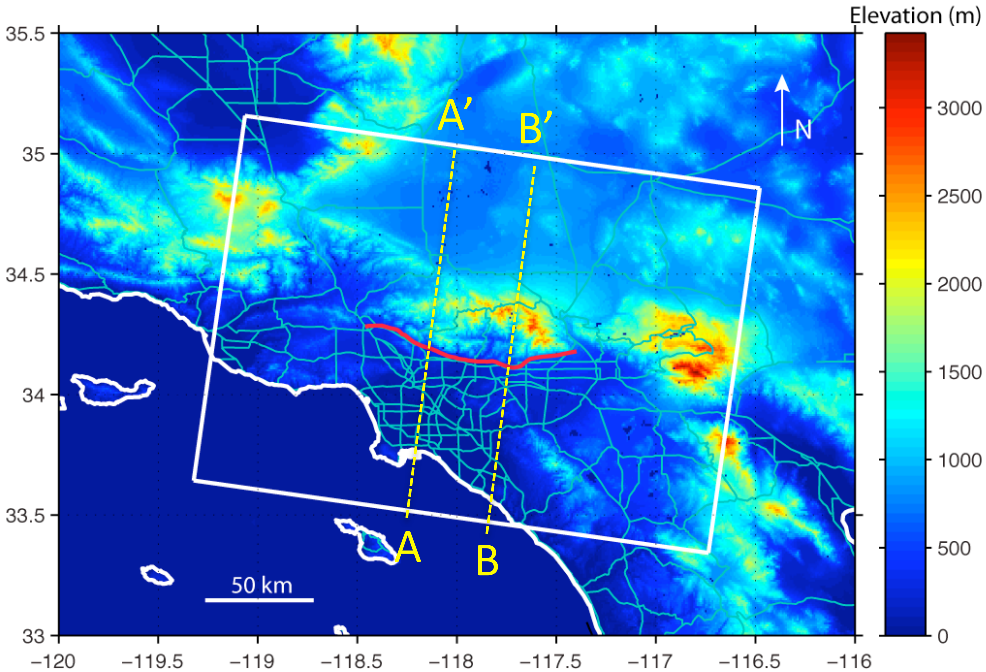
> 69,000 deaths

Hubbard and Shaw (2009)

Fault Geometry (SCEC CFM 3.0)







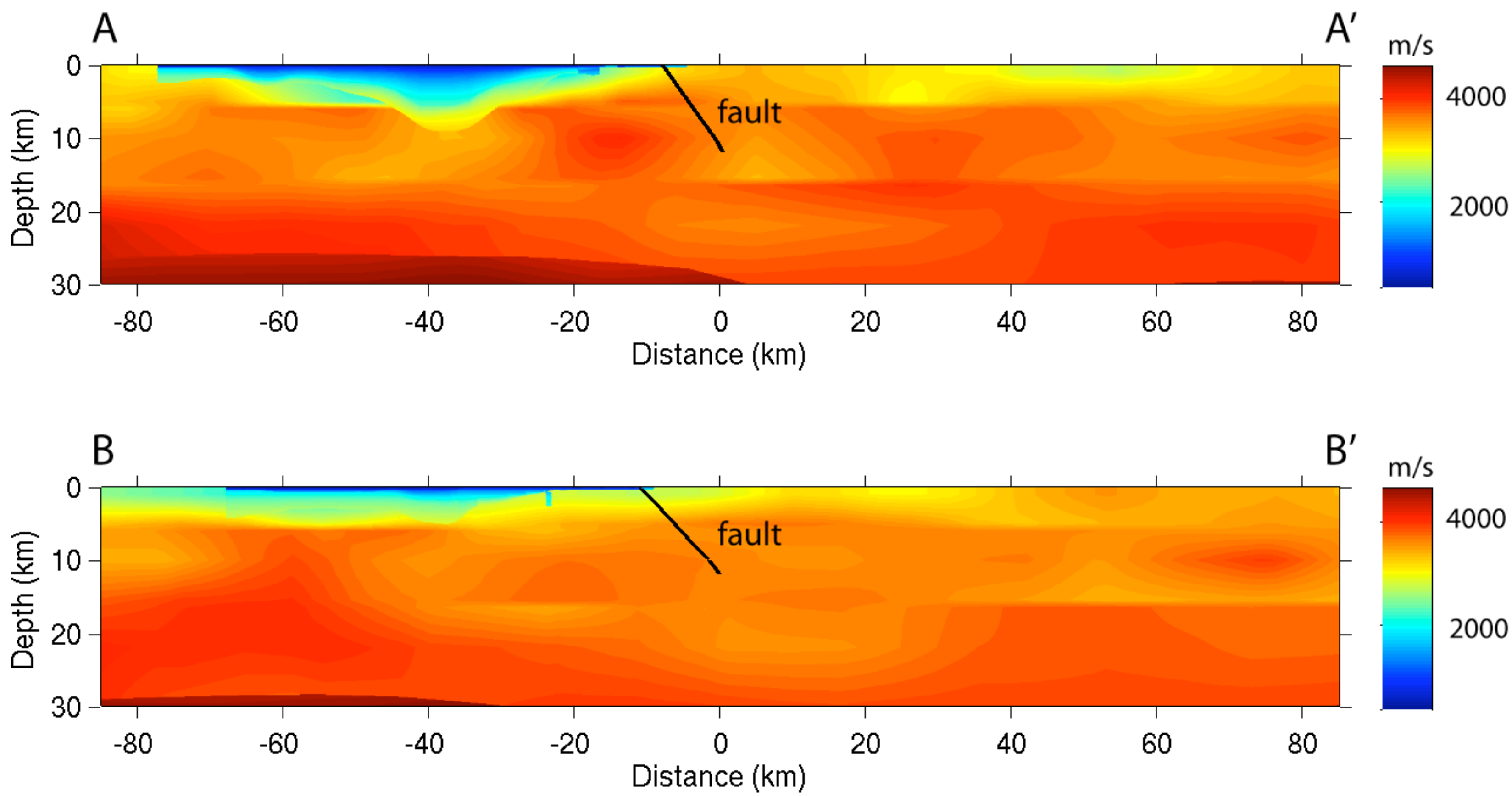
Finite Element Simulation

240 km x 170 km x 30 km

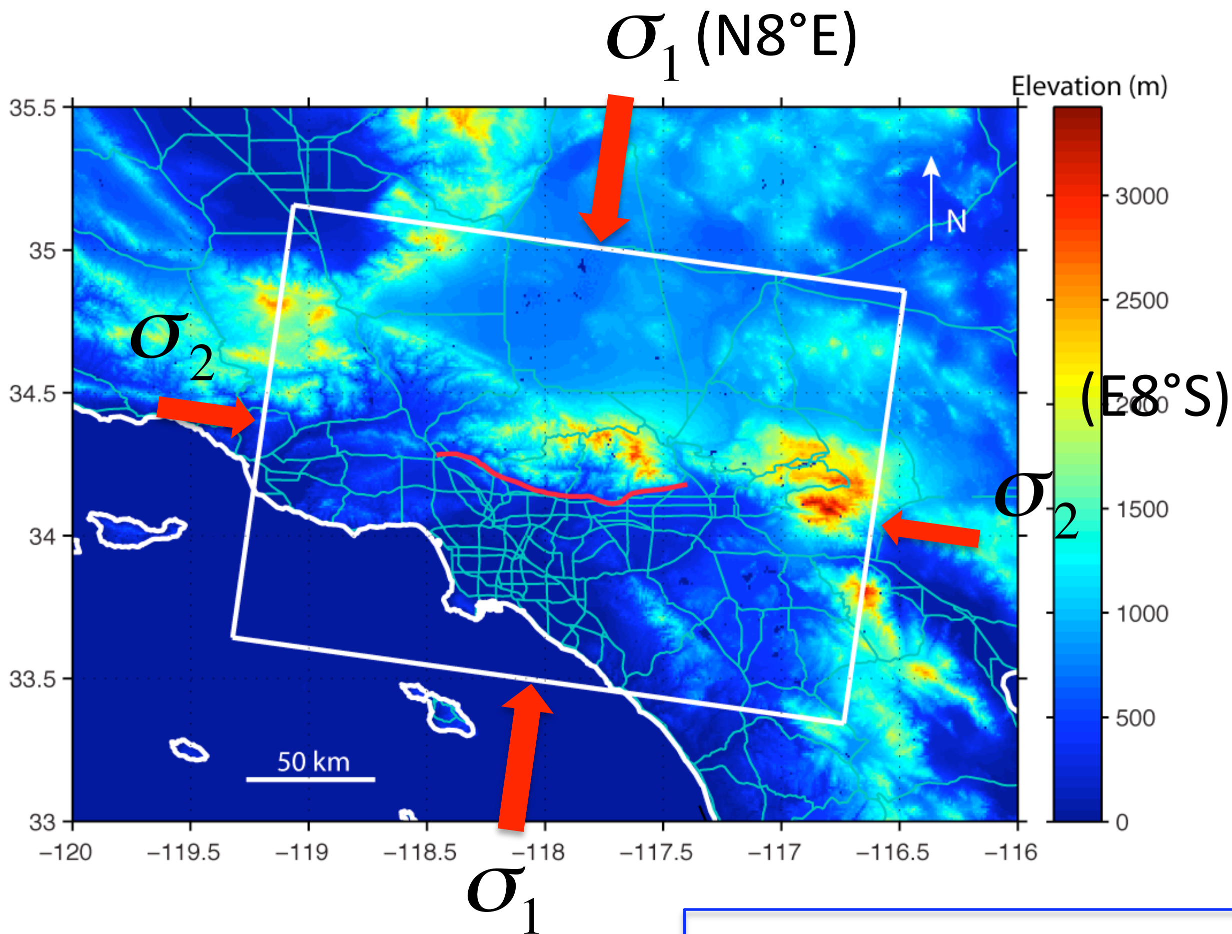
~ 1.2 billion elements

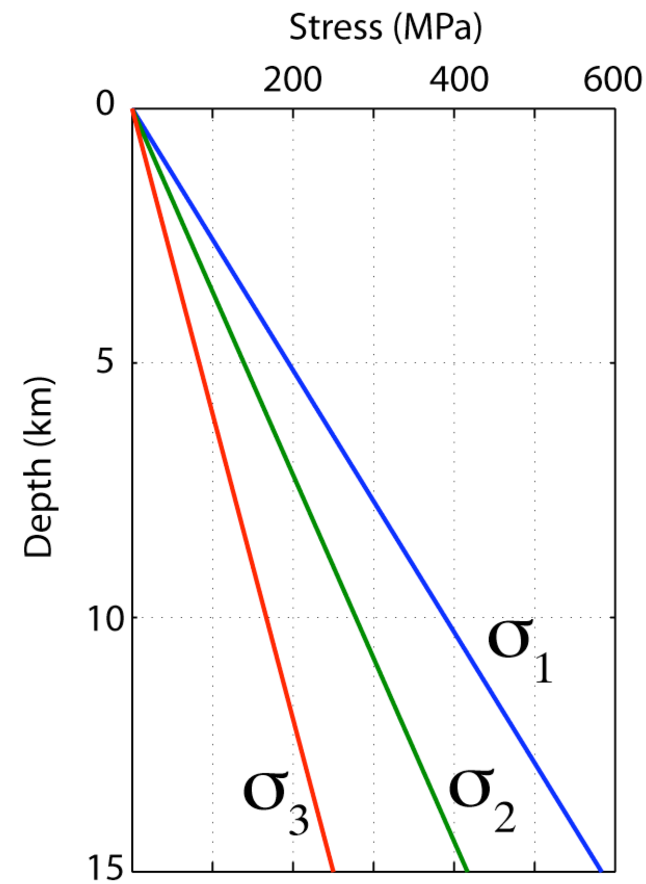
- Code: MAFE
- Structured mesh
- Element size: ~ 100 m
- Minimum V_s: 500 m/s
- Maximum frequency: 0.5 Hz

S-wave Velocity (SCEC CVM 4.0)



Tectonic Loading



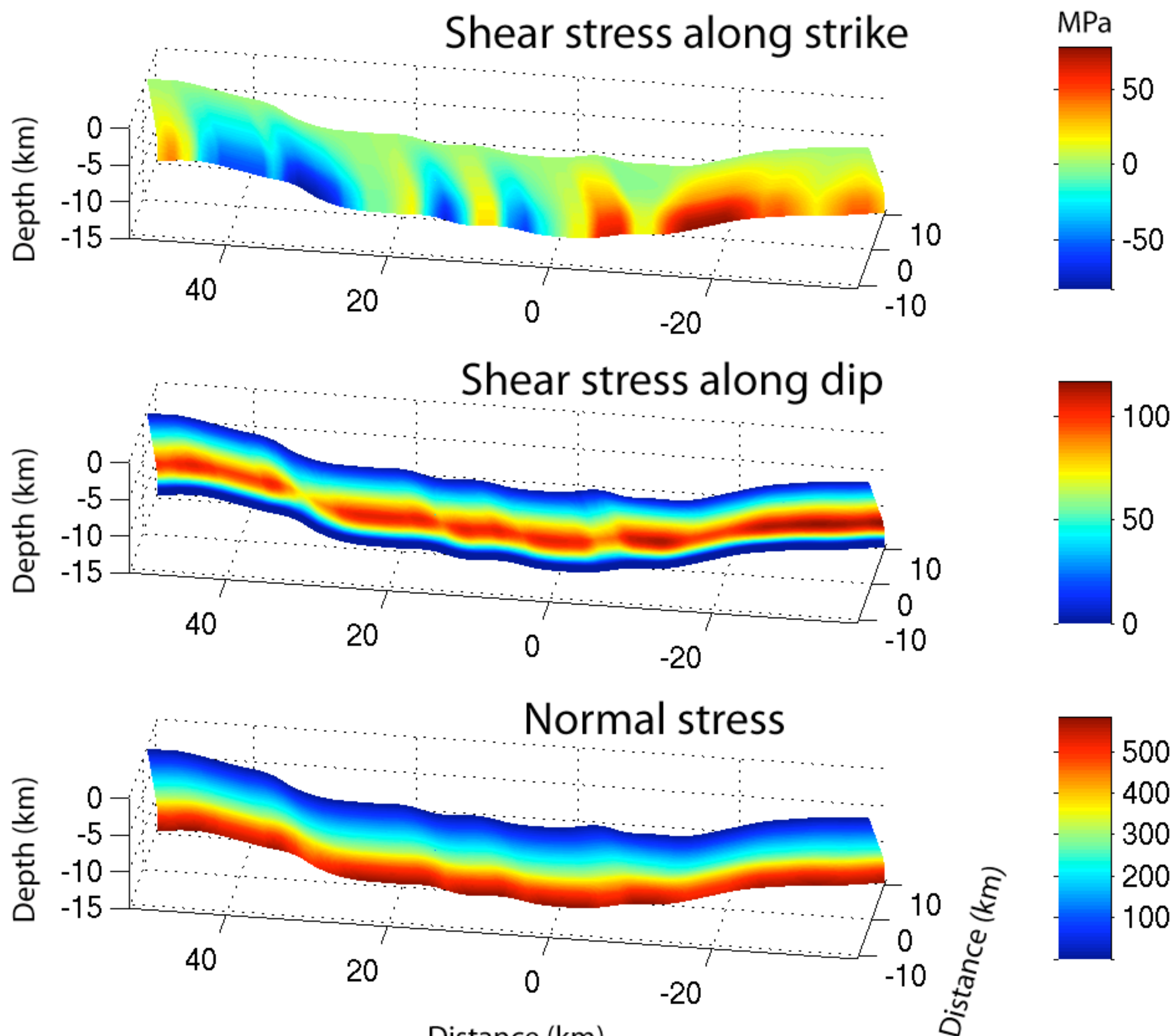


σ_1 : 38.87 MPa/km

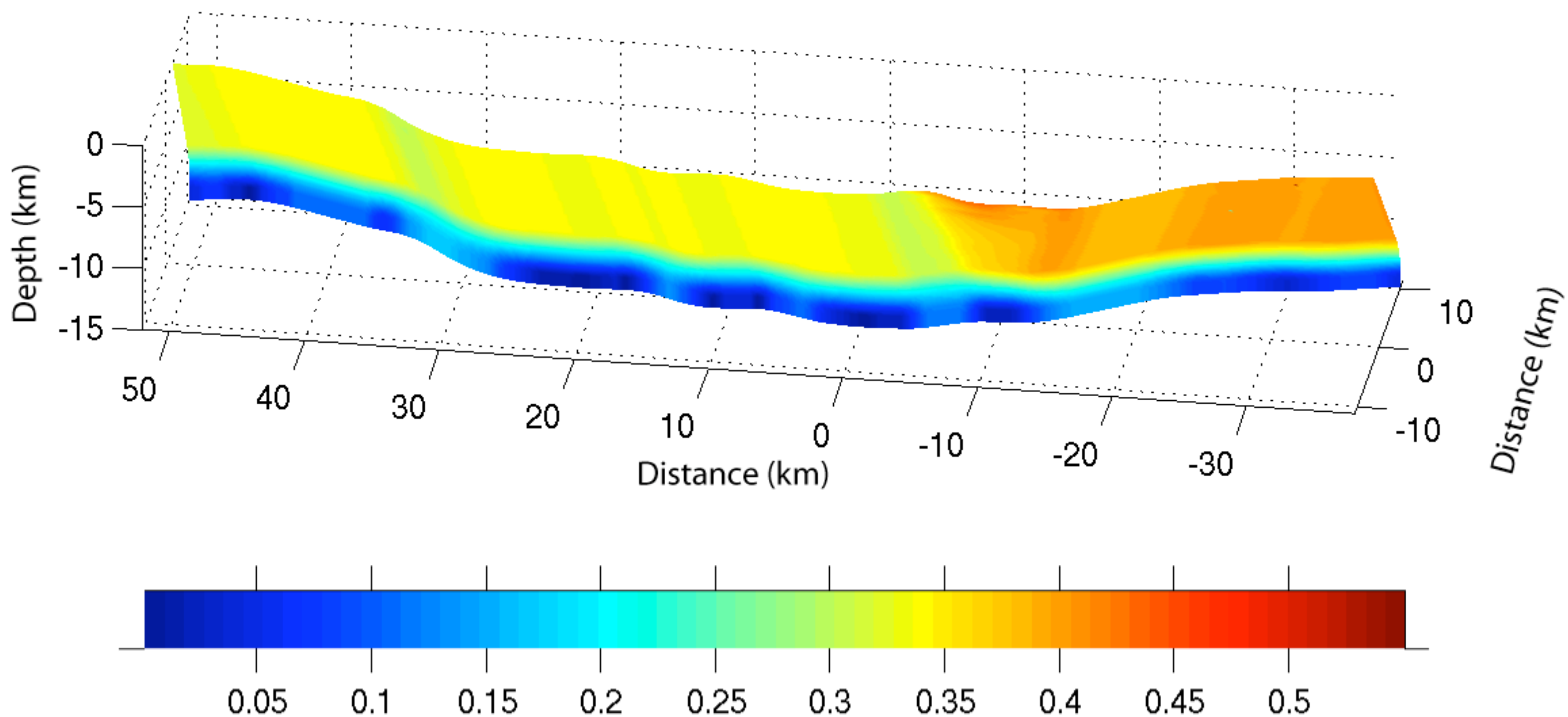
σ_3 : 16.66 MPa/km

$$\sigma_2 = (\sigma_1 + \sigma_3)/2$$

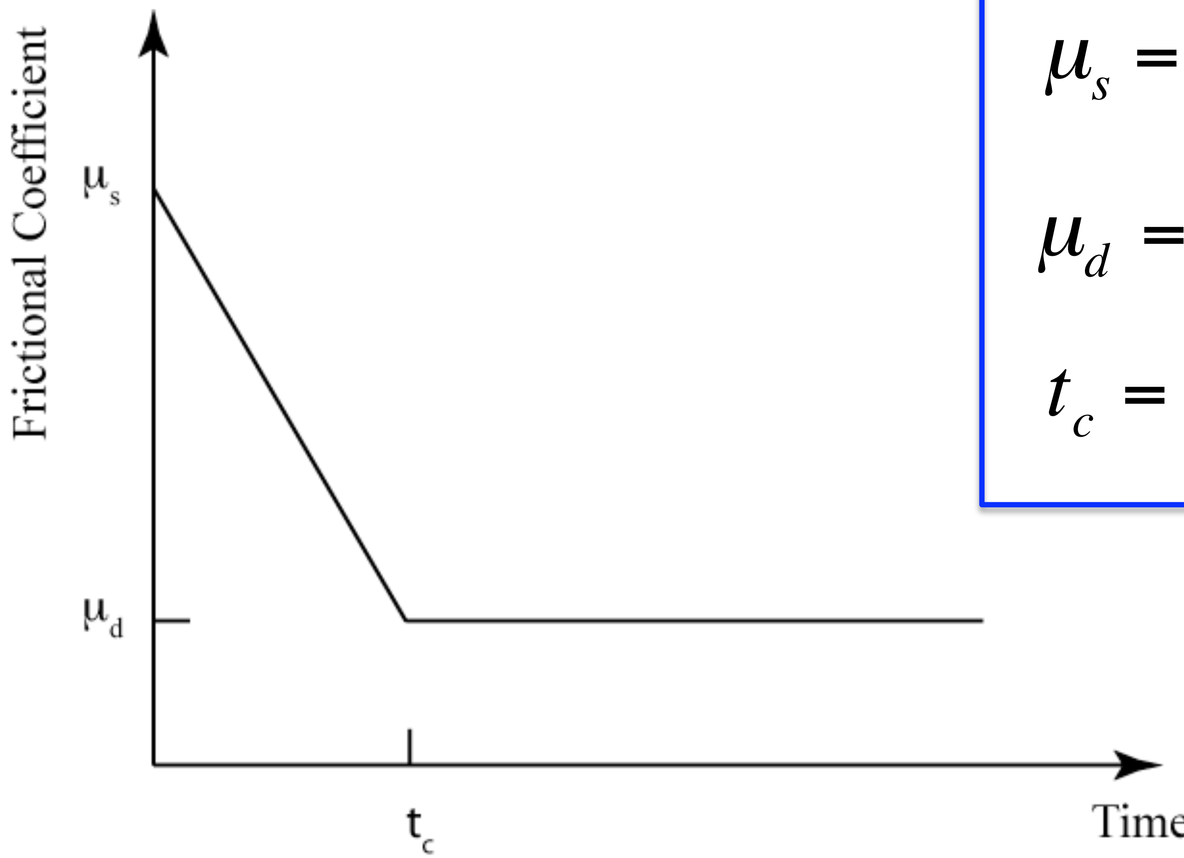
Initial Stresses on Fault



Initial Friction Coefficient on Fault



Time-Weakening Friction



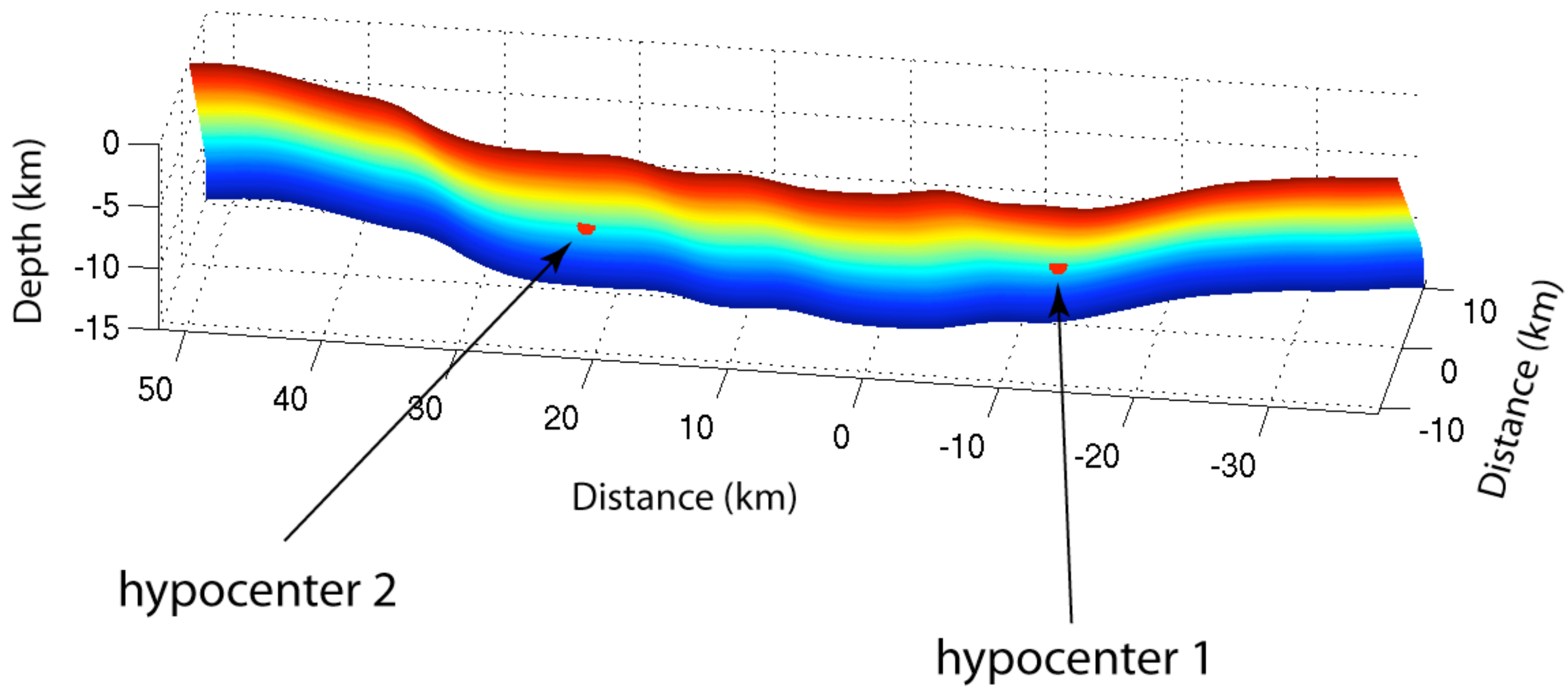
$$\mu_s = 0.55$$

$$\mu_d = 0.25$$

$$t_c = 0.15\ s$$

Andrews (2004)

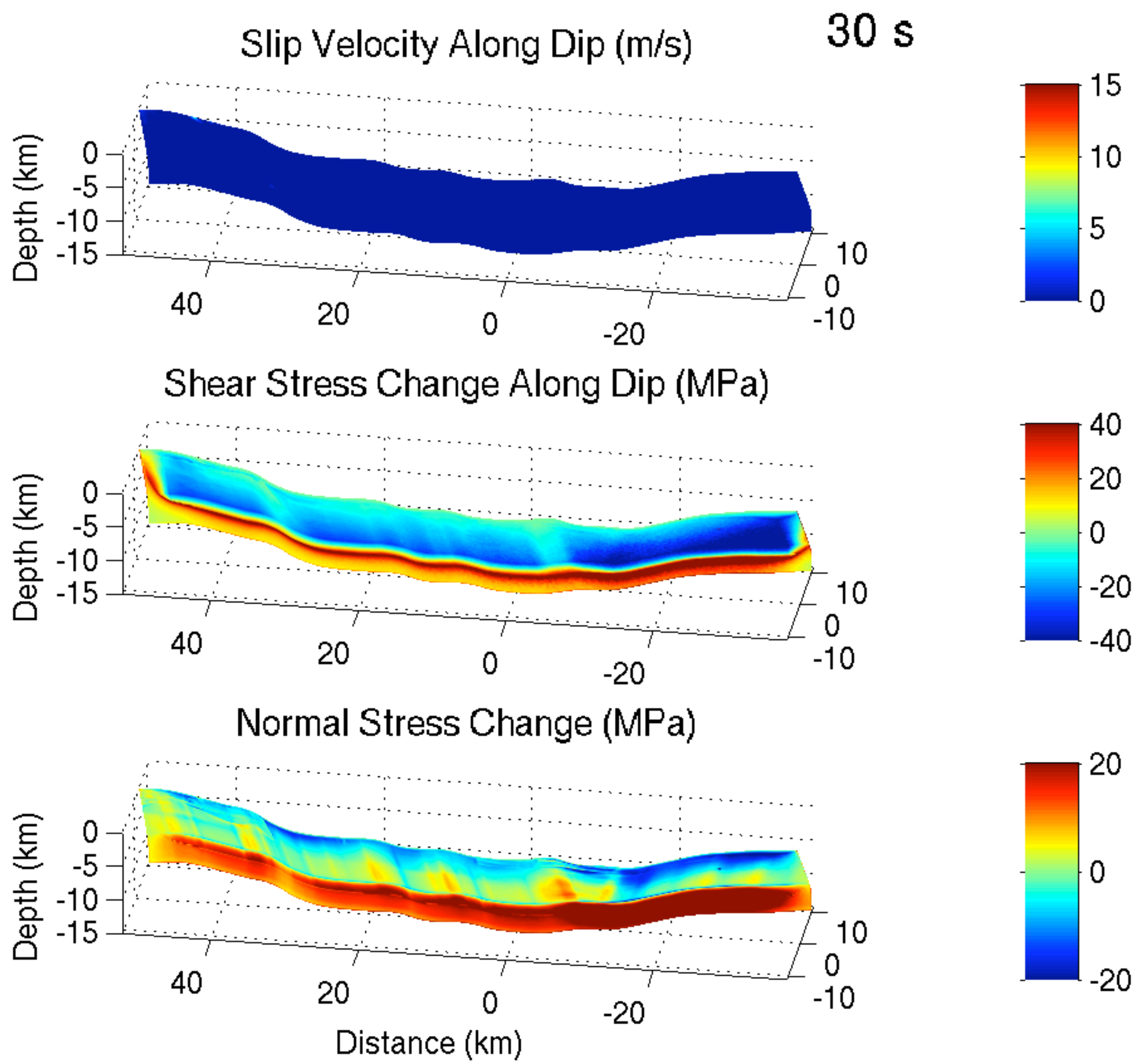
Two Rupture Scenarios



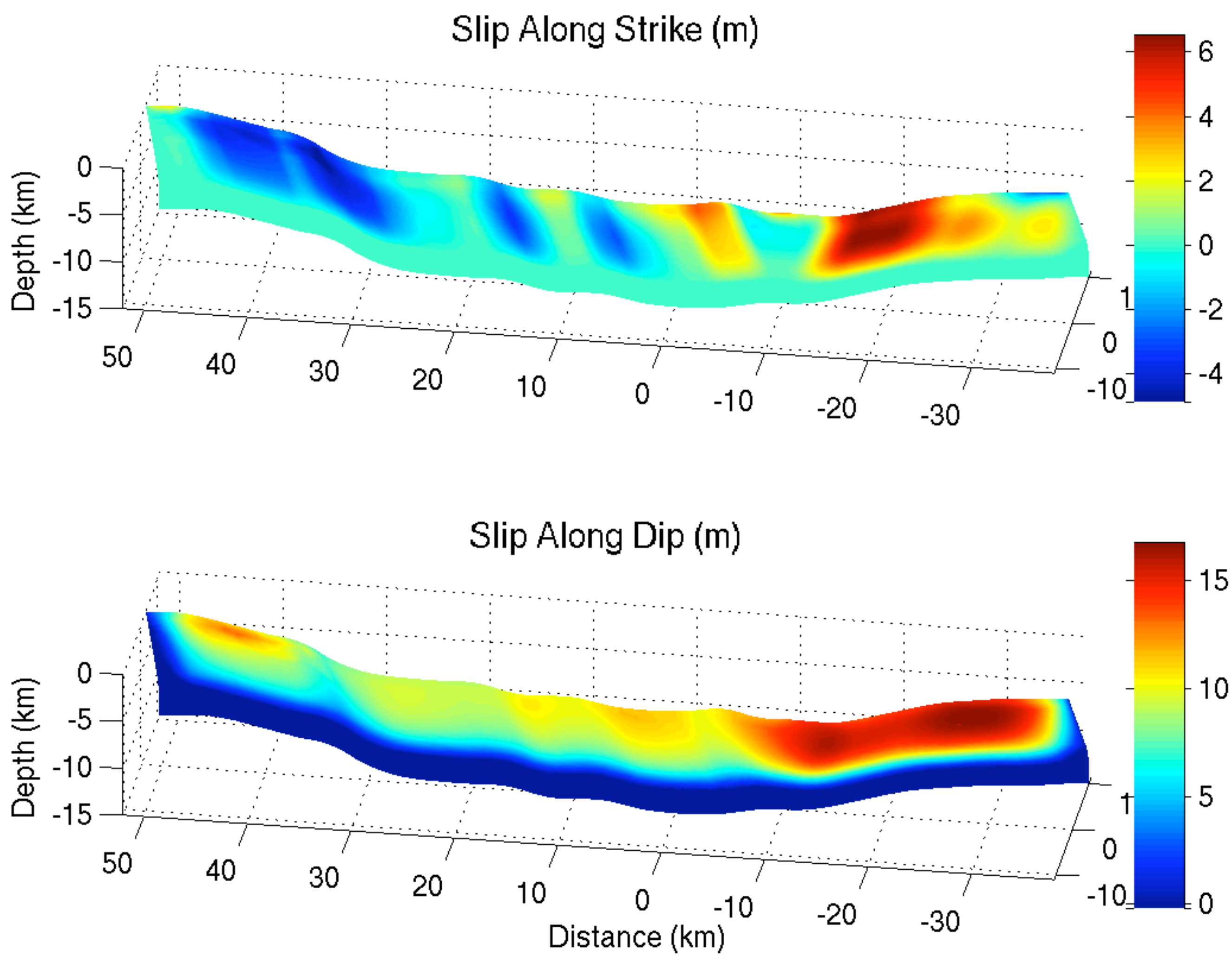
Hypocentral depth : 9 km

Rupture is nucleated by enforcing an initial speed of 2 km/s from the hypocenter.

Rupture Snapshots



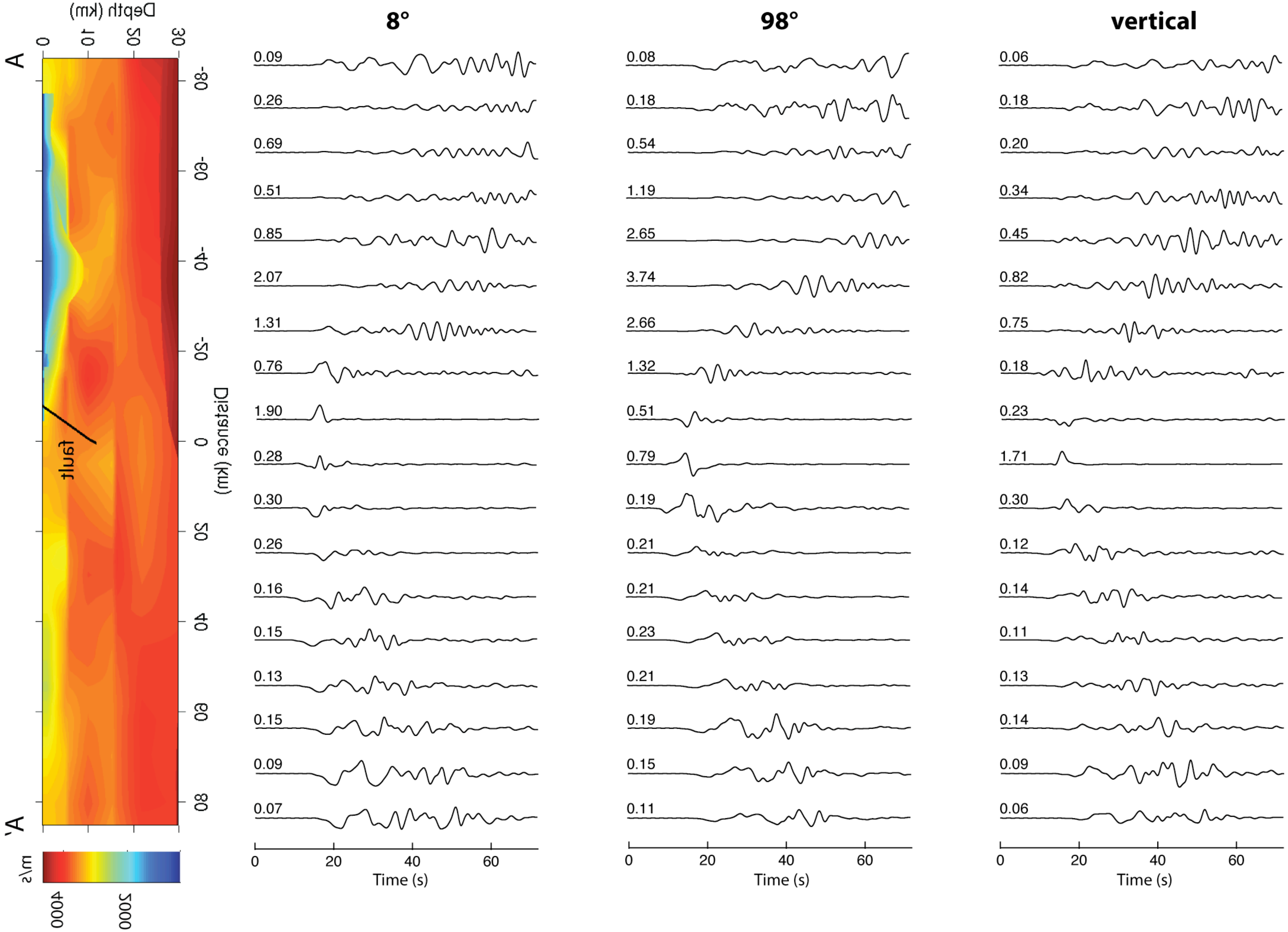
Final Slip Distribution



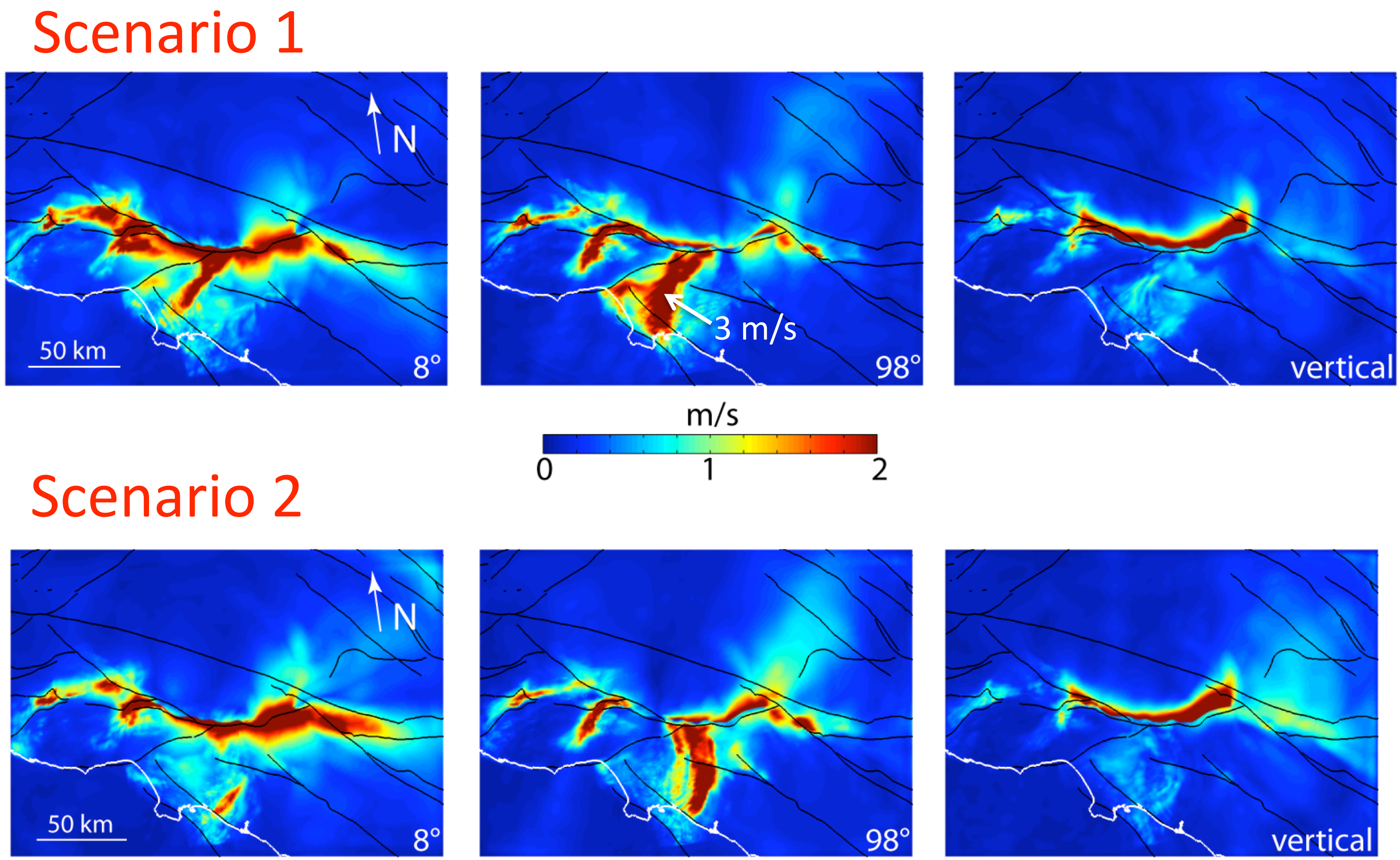
Strong rake rotation

$M_W = 7.7$

Velocity Time Histories Along A-A’



Peak Ground Velocity



Interesting Topics:

1. More realistic friction laws
2. Thermal effect on friction
3. Pore fluid effect
4. Plastic deformation
5. Finite deformation
6. …

Thanks!

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