Modeling earthquake source processes: From tectonics to dynamic rupture

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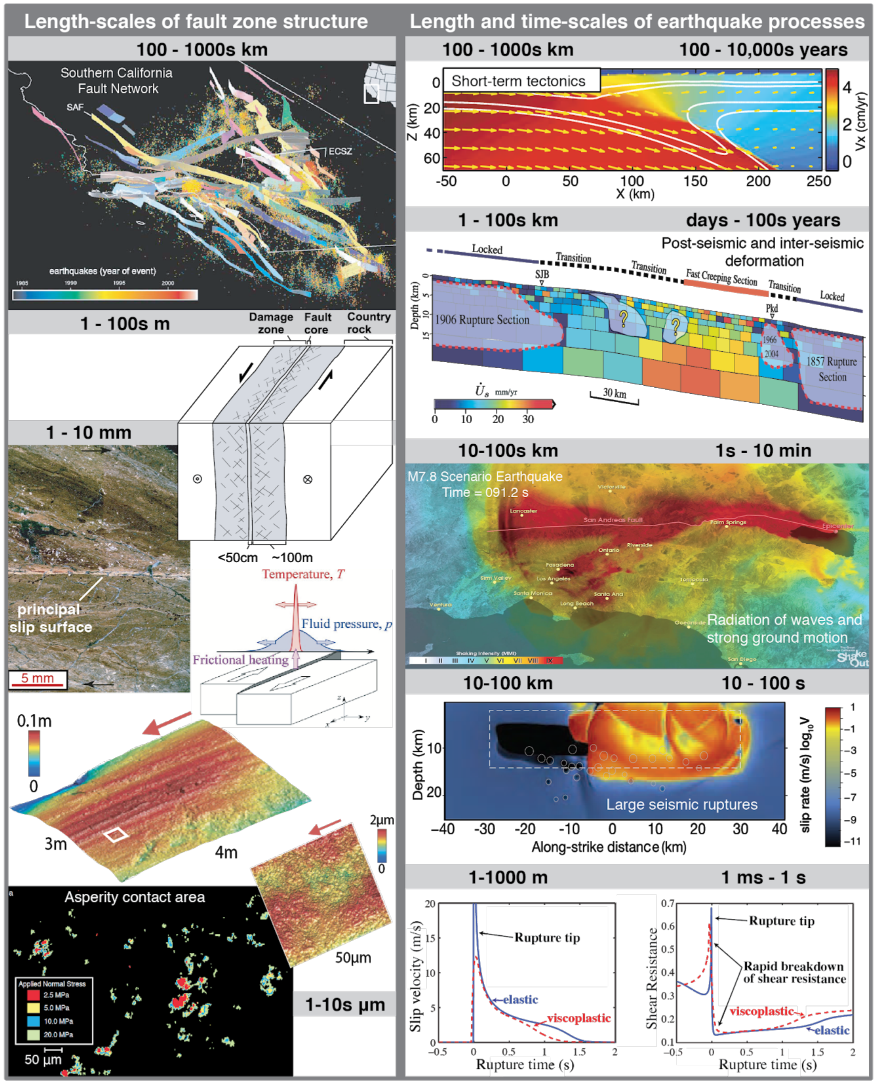
- Multiple coupled spatial scales (1 micron to 1,000 km):
  shear zone/fault core, damage zone,
  deeper fault extensions/ductile transition,
  fault segments/networks;
- Multiple coupled temporal scales (1 ms to 100,000 yr):
  dynamic rupture, interseismic periods,
  earthquake sequences, short-term tectonics;
- Multiple coupled physical and chemical factors:
  fluid effects, both physical and chemical,
  time-dependent processes of damage/healing and flow,
  realistic geometry/roughness, heterogeneity.

Plesch et al., 2007; Mitchell and Faulkner, 2009; Chester and Chester, 1998; Candela and Brodsky, 2016; Dieterich and Kilgore, 1994, van Dinther et al., 2013; Jolivet et al., 2015; Jiang and Lapusta, 2016; Dunham et al., 2011a, and https://earthquake.usgs.gov/learn/topics/shakingsimulations/shakeout/.

www.seismolab.caltech.edu/modeling-earthquake-source-workshop.html



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NSF-sponsored and SCEC-supported workshop and report

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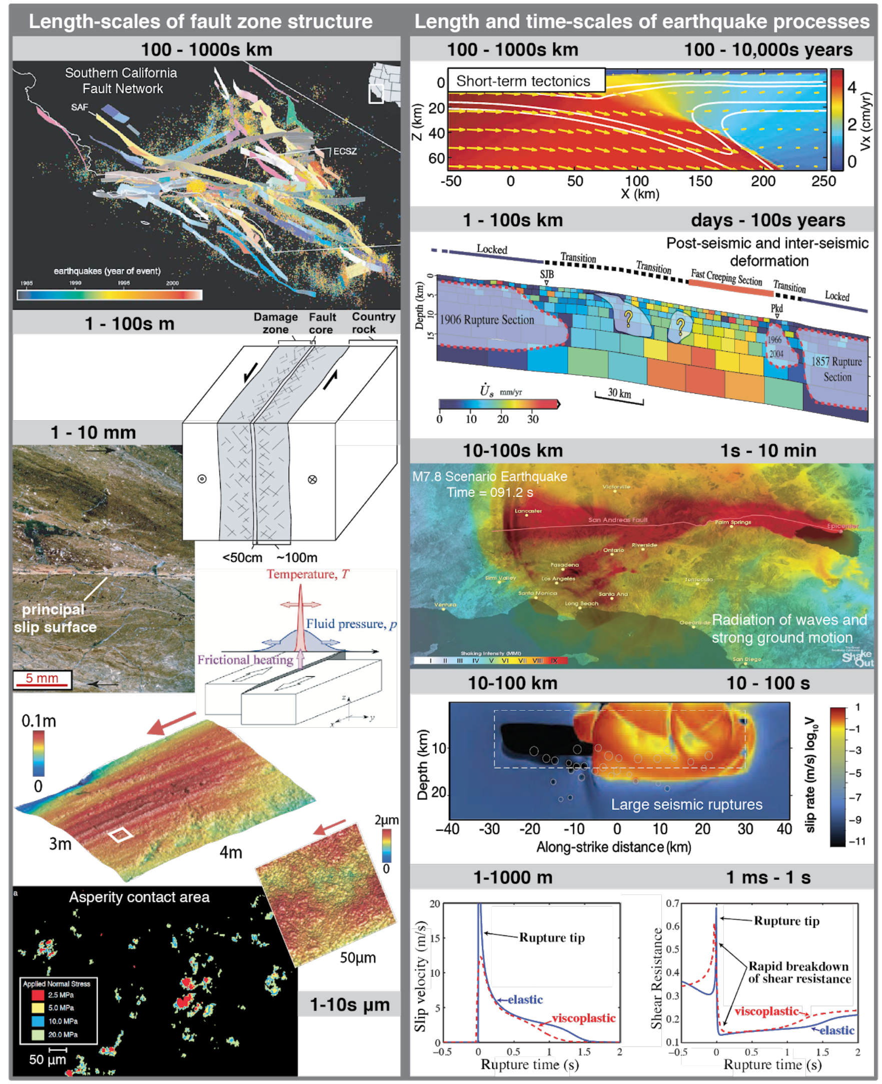
Brad Aagaard, Sylvain Barbot, Thorsten W. Becker, Nicholas M. Beeler, Yehuda Ben-Zion, Gregory C. Beroza, Roland Bürgmann, Emily E. Brodsky, Camilla Cattania, Benchun Duan, Ahmed E. Elbanna, William L. Ellsworth, Brittany A. Erickson, Alice-Agnes Gabriel, Michael Gurnis, Ruth A. Harris, Junle Jiang, Greg Hirth, Yoshihiro Kaneko, James D. Kirkpatrick, Thorne Lay, Shuo Ma, Chris Marone, Gregory C. McLaskey, Men-Andrin Meier, André R. Niemeijer, Hiroyuki Noda, David D. Oglesby, Kim B. Olsen, Ares J. Rosakis, Zachary E. Ross, Christie D. Rowe, Paul Segall, Yuval Tal, John Townend, John E. Vidale, Zhongwen Zhan, Wenlu Zhu



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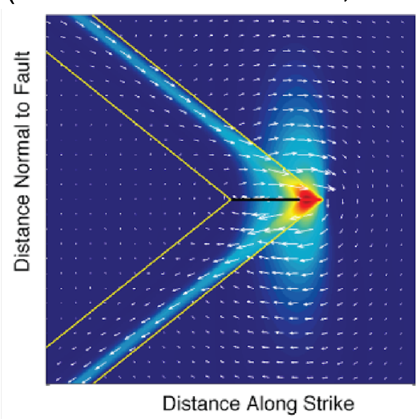
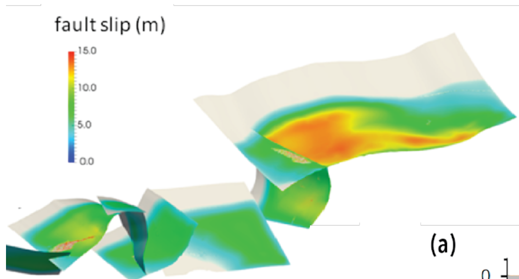
Multiple successes of earthquake source modeling

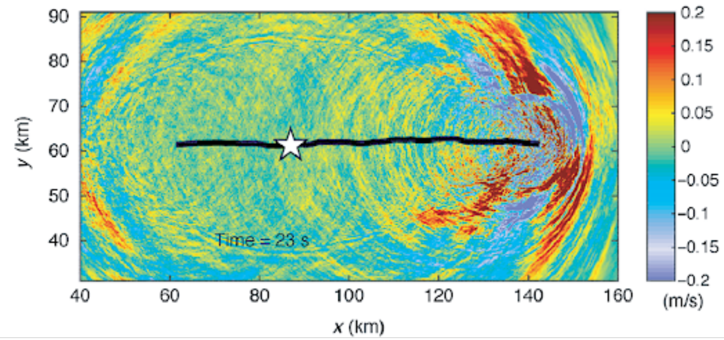
Supershear rupture
(Dunham and Archuleta, 2005)



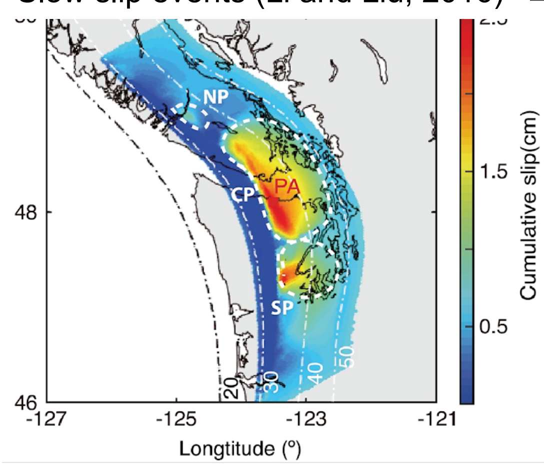
2016 Mw 7.8 Kaikoura earthquake
(Urich, Gabriel et al., 2018)



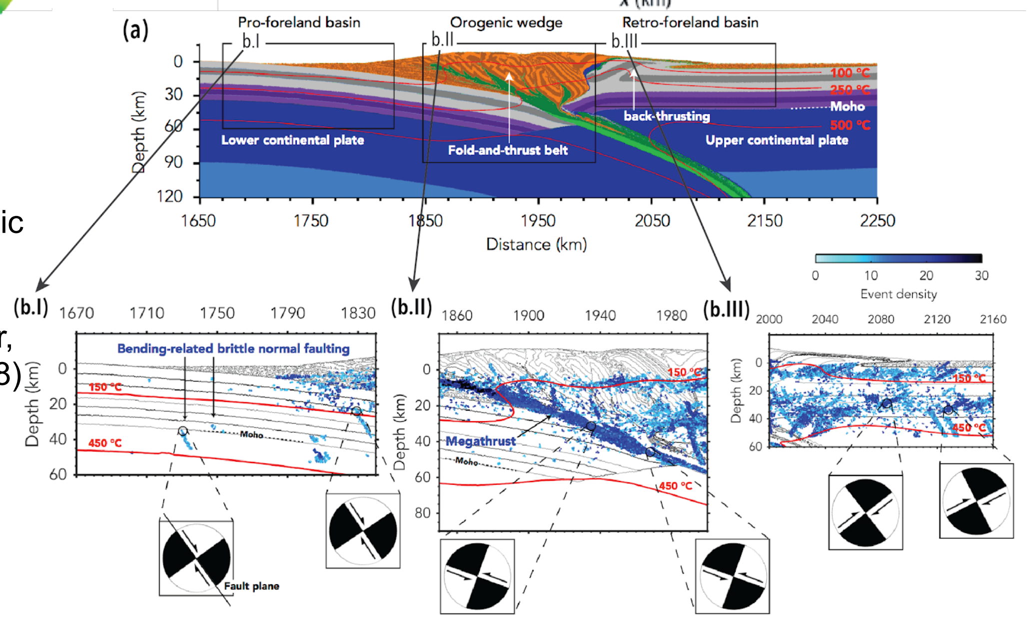
Radiation from rough faults (Withers et al., 2008)



Slow slip events (Li and Liu, 2016)



From tectonic
to seismic
(Dal Zilio,
van Dinther,
Gerya, 2018)



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Several coupled physical factors affect how ruptures nucleate, propagate, and arrest

Problem statement: Solving equations of motion in the surrounding bulk with the boundary condition

Fault stress = Fault resistance

Fault stress = tectonic loading + stress transfer

Fault resistance: depends on normal stress, pore fluid pressure, slip rate, temperature, and histories

Tectonic loading:

Backslip

Realistic loading

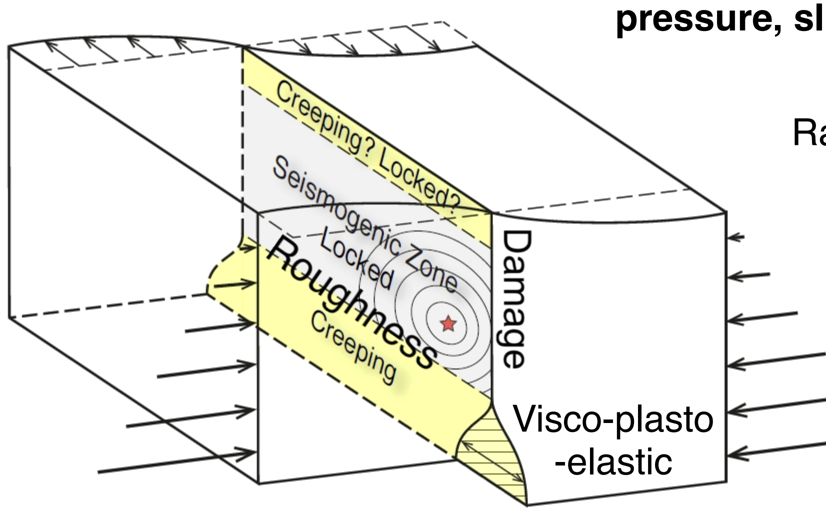
Stress transfer:

Static due to seismic slip

Static due to aseismic slip

Wave-mediated (dynamic) during seismic slip

Due to fluid flow (e.g., dehydration reactions, or deformation-induced)



Bulk rheology

Uniform elastic

Layered elastic

Bi-material elastic

3D elastic

Rate-and-state friction at low slip rates

Pore fluid pressure evolution due to shear dilatancy/compaction at slow slip rates

Enhanced dynamic weakening at high slip rates (shear heating):

Thermal pressurization of fluids

Poroelastic effects during sliding

Evolving off-fault damage

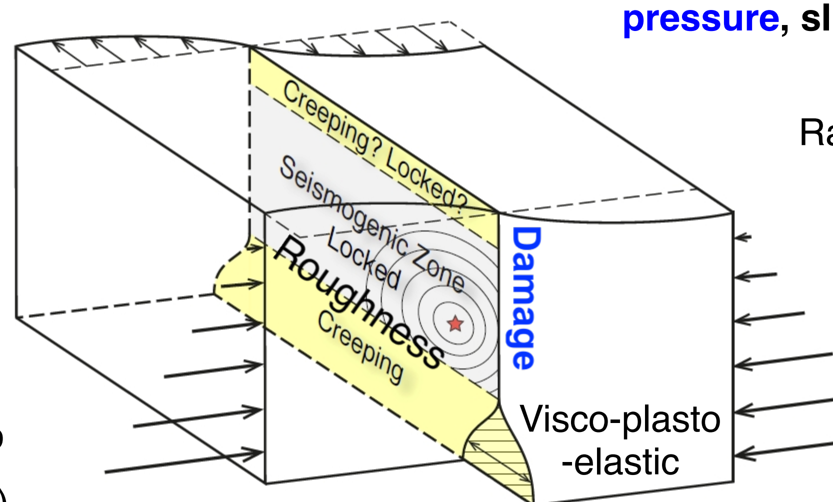
Healing (cooling/fluids/chemical)

Point #1: Fluids may dominate the response => Need computational methods for coupled deformation/failure and fluid flow

Point #2: Small scales matter => need multiscale computational methods

Fault stress = **tectonic loading** + **stress transfer**

Fault resistance: depends on normal stress, pore fluid pressure, slip rate, temperature, and histories



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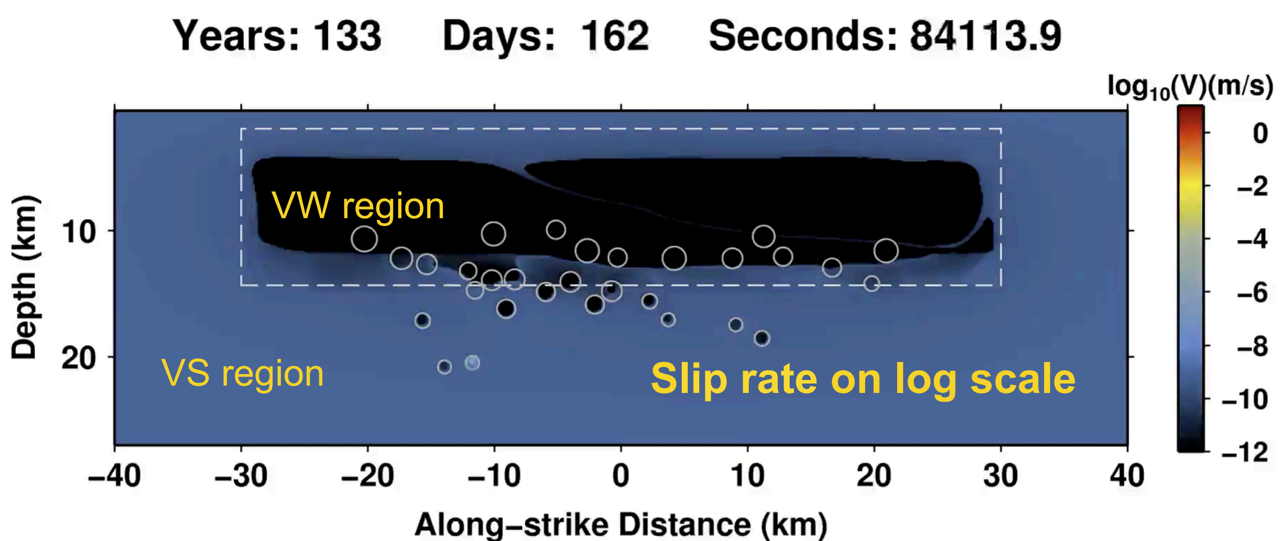
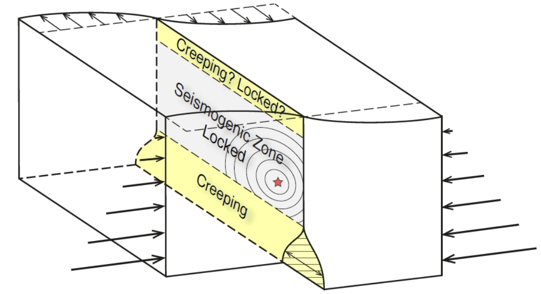
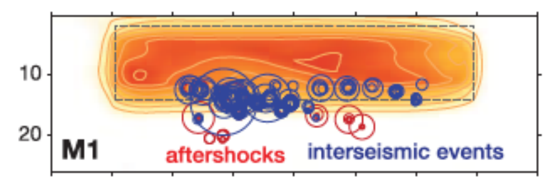
Simulations of earthquake sequences and slow slip on a strike-slip fault with highly localized shear zone







Lab-derived rate-and-state friction

$$\tau = (\sigma - p)[f_o + a\ln\frac{V}{V_o} + b\ln\frac{V_o\theta}{L}]$$

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

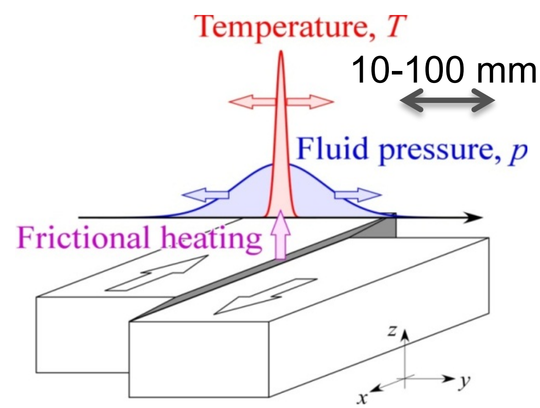
Dieterich (2007)
and references therein

Thermal pressurization of pore fluids

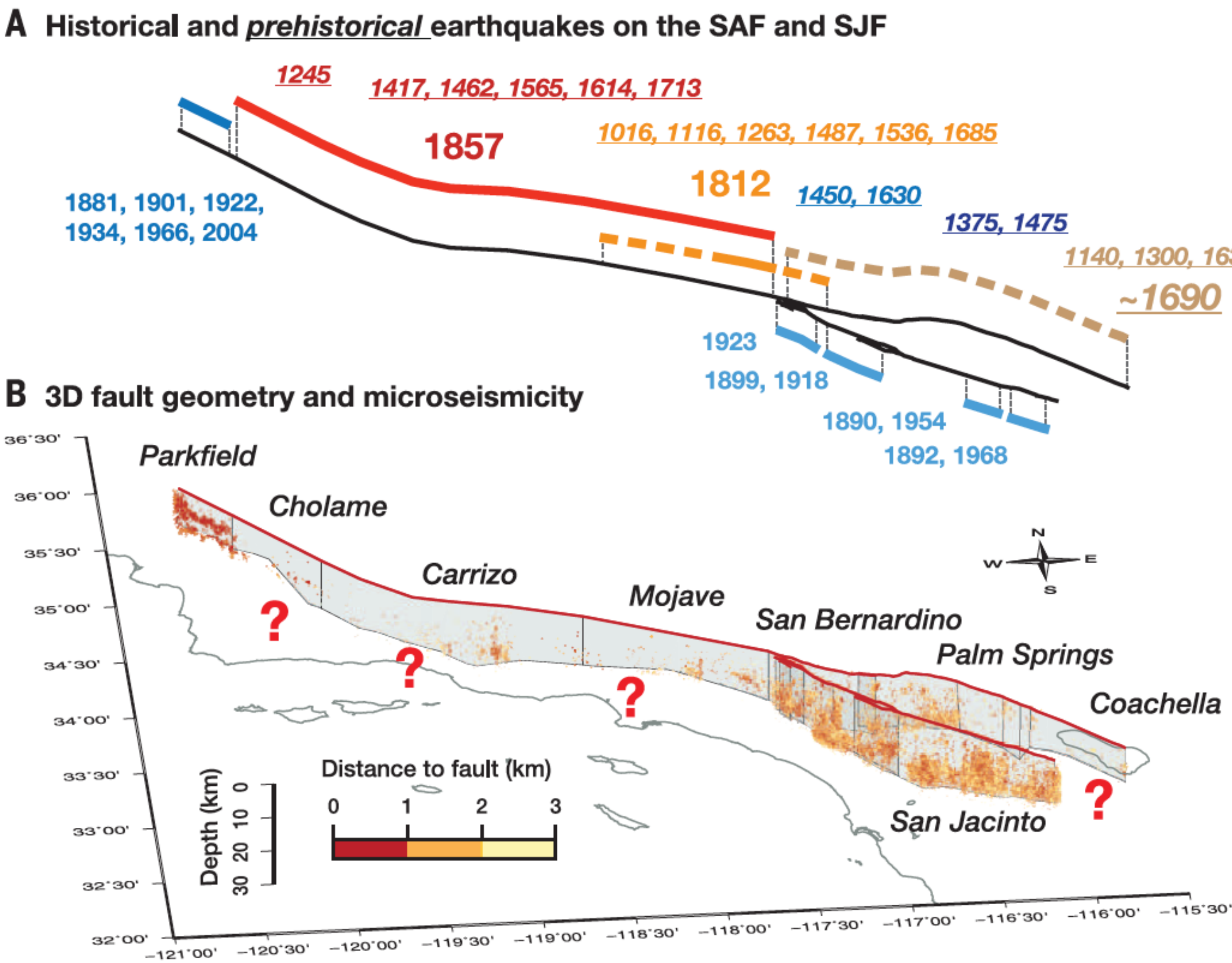
$$\frac{\partial p}{\partial t} = \alpha_{hy}\frac{\partial^2 p}{\partial y^2} + \Lambda\frac{\partial T}{\partial t}$$

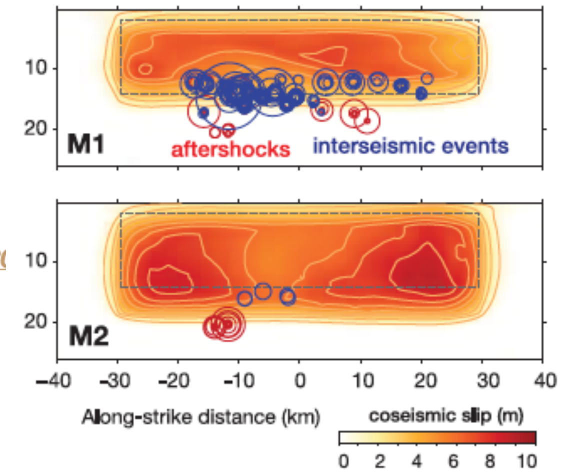
$$\frac{\partial T}{\partial t} = \alpha_{th}\frac{\partial^2 T}{\partial y^2} + \frac{\tau V}{\rho c}\frac{exp(-y^2/2w^2)}{\sqrt{2\pi}w}$$

Rice (2006)
and references therein



Jiang and Lapusta, 2016





No microseismicity at the base of seismogenic zone <=>

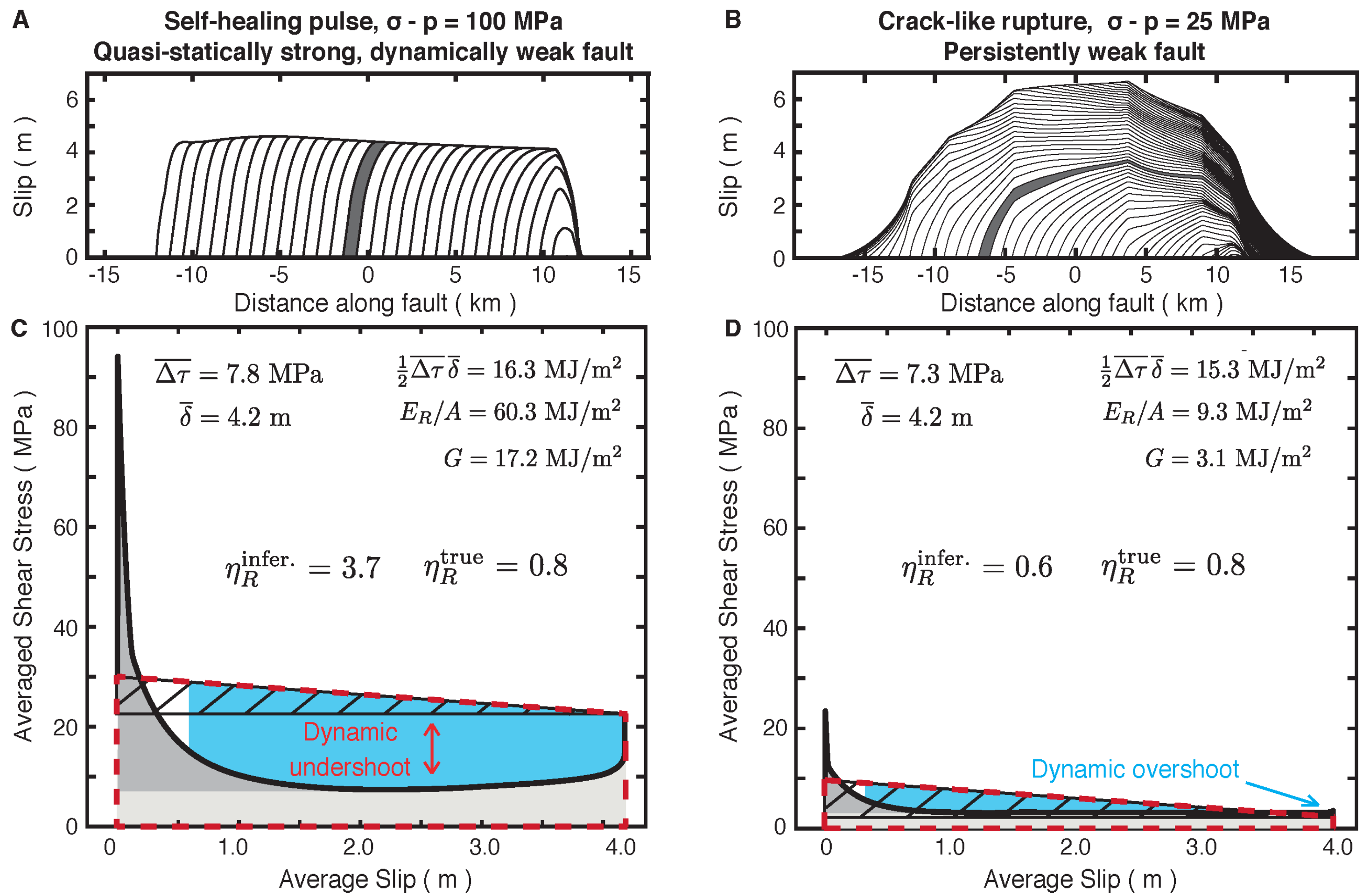
deeper penetration of large events

Jiang and Lapusta, 2016

Low-heat mature faults:

Co-seismically weak due to rapid shear heating?

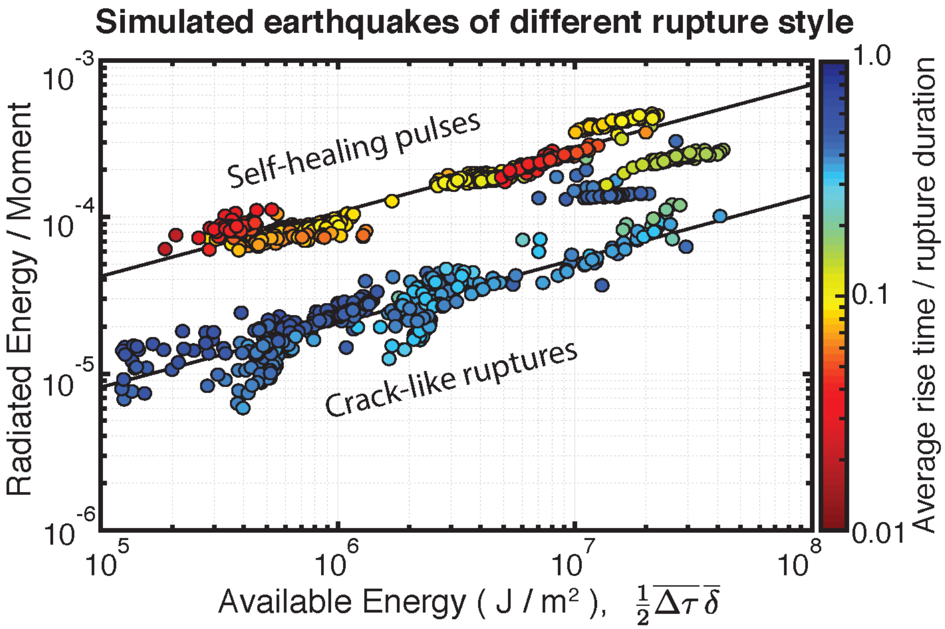
Chronically weak due to persistent fluid overpressure?

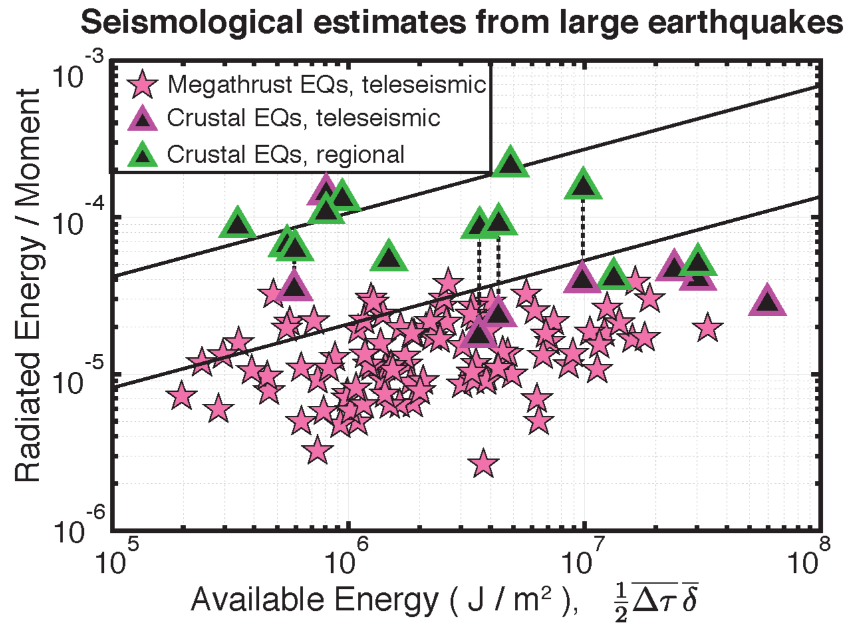


Self-healing pulses have much higher radiated energy for the same slip, stress drop, and moment.

Lambert, Lapusta, and Perry
in revision

Are megathrusts chronically weak and host crack-like ruptures whereas mature crustal faults dynamically weak and host self-healing pulses?



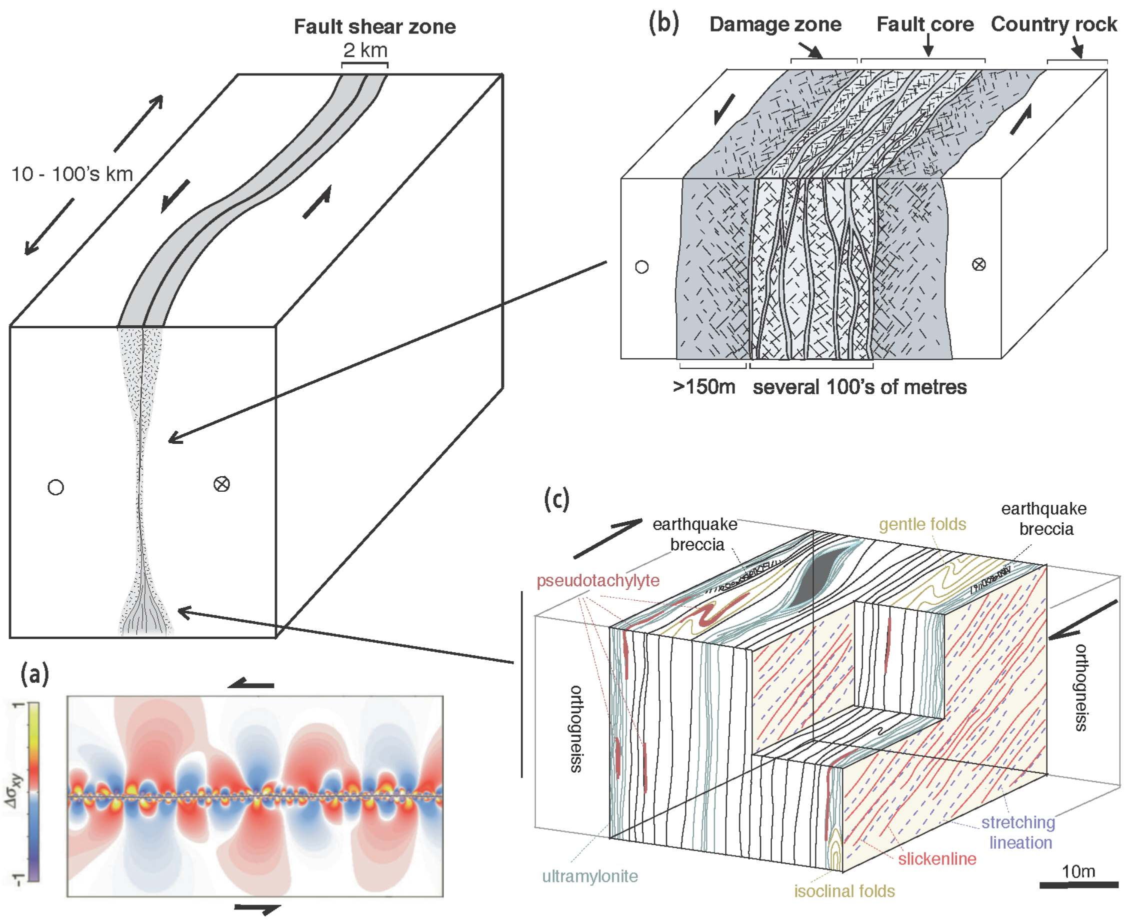


Need to check/improve radiated energy estimates

Need to confirm the conclusions with more sophisticated modeling

Lambert, Lapusta and Perry, in revision

Point #3: Scales between lab (< 0.1 m) and modeling discretization (> 100 m) matter
=> Need comp. tools for developing scale-appropriate constitutive relations



How do we capture the evolving shear localization structure and hydromechanical properties over 0.1 – 100 m scales?

(a) Local fault roughness on scales comparable to slip: local stress changes, damage, fluid flow etc

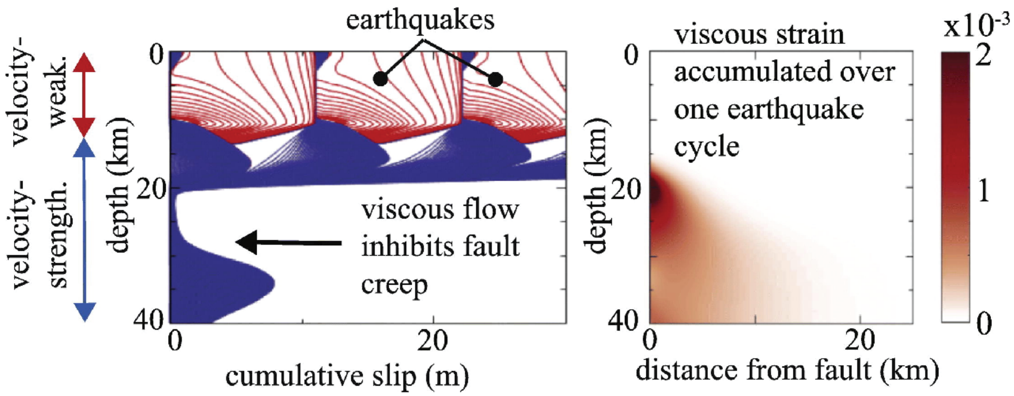
(b) Fault normal structure with multiple shear layers and evolving damage

(c) Variations in lithology, grain size, fabric, and architecture below seismogenic depths

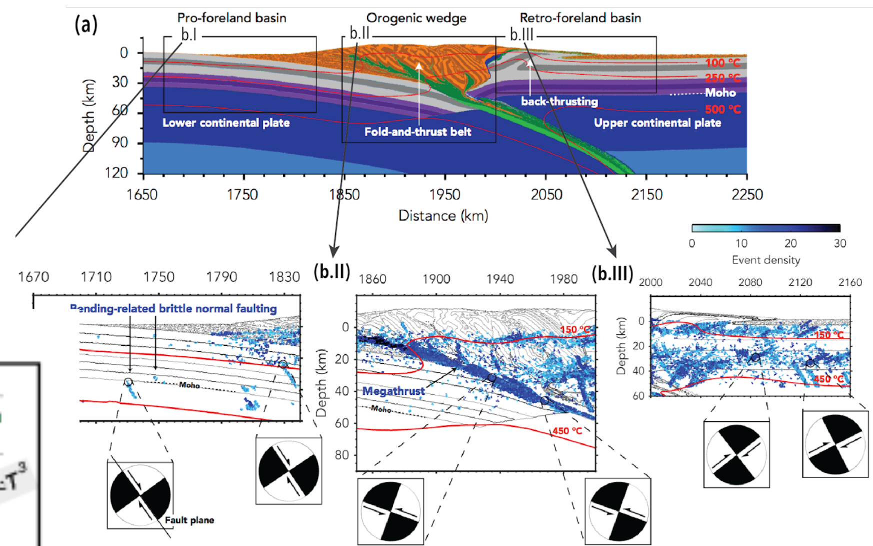
=> Lab experiments on 0.01-1 m +
Numerical experiments on 1-100 m

Dieterich and Smith, 2009; Mitchell and Faulkner, 2009; Melosh et al., 2018

Point #4: Keep developing models with realistic visco-elasto-plastic rheologies + realistic elastodynamics (wave-mediated effects) + fluid flow from point #1

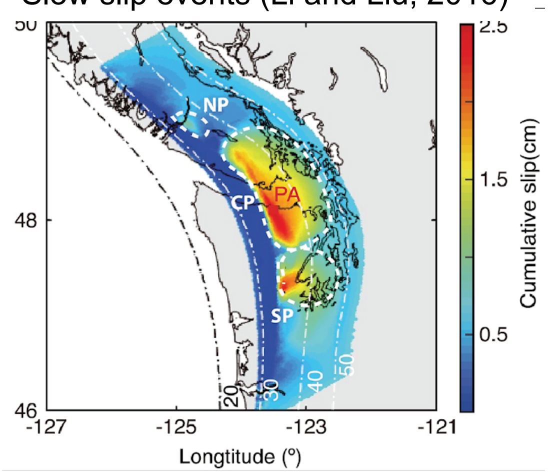


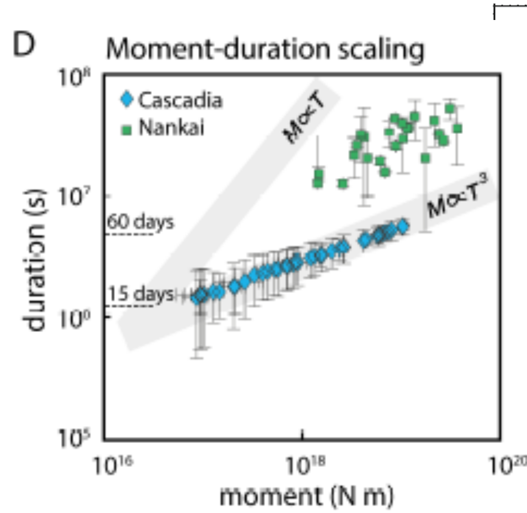
Allison and Dunham, 2018



Dal Zilio, van Dinther, Gerya, 2018

Slow slip events (Li and Liu, 2016)



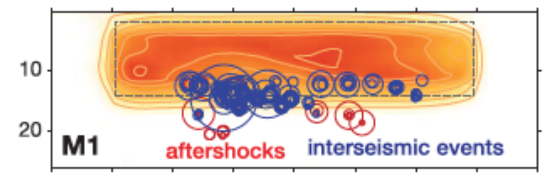


Dal Zilio, Lapusta, Avouac, 2020

Modeling earthquake source processes and dynamic rupture

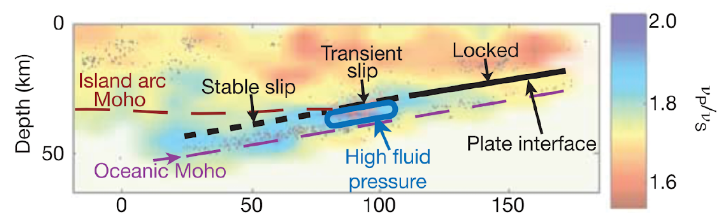
Modeling earthquake rupture allows us to:

- Study interaction of faulting at different temporal/spatial scales
- Supplement field observations by lab and theoretical findings



What we would like to do:

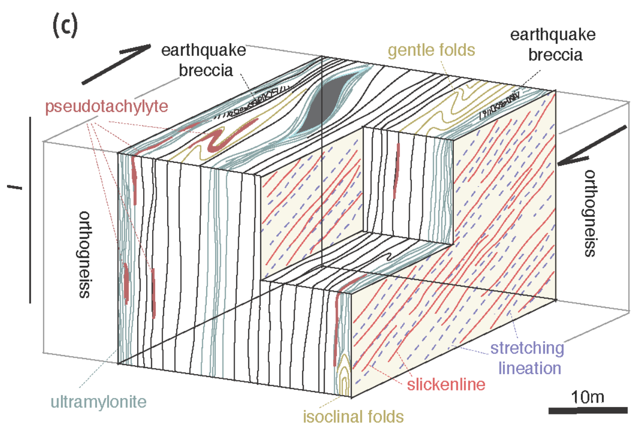
- Predict the source component of strong ground motions
- Improve our understanding of potential large/extreme events
- Identify key gaps in knowledge, including observations



We need computation methods for:

1. Coupling deformation/failure and fluid flow
2. Multiscale simulations that account for small scales
3. Numerical experiments at 1-100 m scale
   to derive meso-scale constitutive laws for faults and bulk
4. Modeling with realistic visco-elasto-plastic rheologies
   + realistic elastodynamics (wave-mediated effects) + fluids

All for simulating sequences of earthquakes + aseismic slip/deformation in non-planar fault geometries

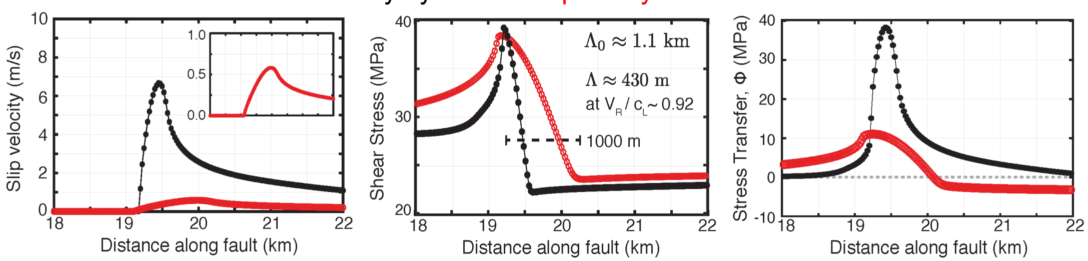


Jiang and Lapusta, 2016;
Shelly et al., 2016; Melosh et al., 2018

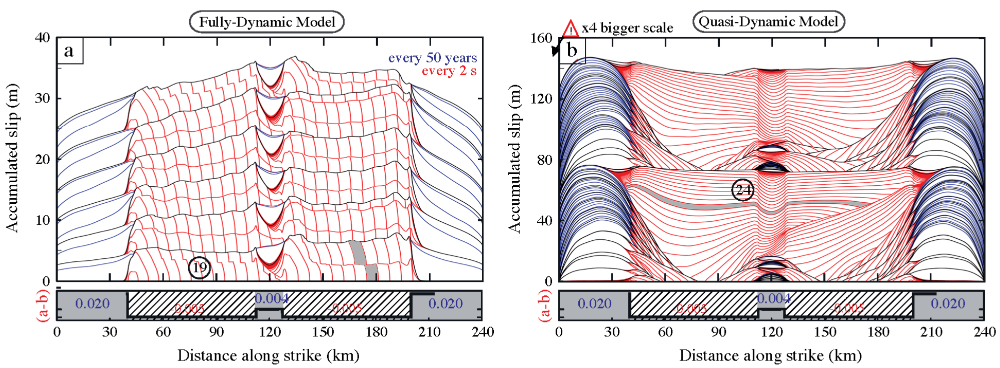
Importance of wave-mediated stress effects during seismic events

Quasi-dynamic vs. fully dynamic simulations result in substantially different rupture kinematics, stress evolution and stress transfer

Fully dynamic vs. quasi-dynamic

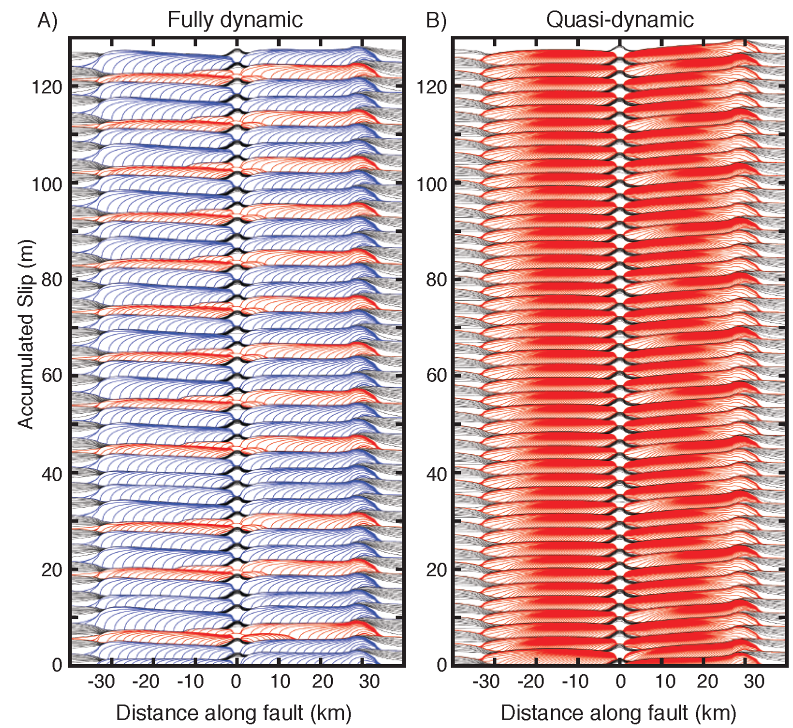


and substantial differences for fault models with strong rate-dependent behavior



Thomas et al., 2014

Leading to different interactions of fault segments



Lambert and Lapusta, in prep