SCEC Mission

Gather data on earthquakes in Southern California and elsewhere

▶ Integrate this information into a **comprehensive, physics-based understanding of earthquake phenomena**

▶ Communicate this understanding to end-users and society at large as useful knowledge for reducing earthquake risk

SCEC4 Proposal:

Six Fundamental Problems in Earthquake Physics

- Stress transfer from plate motion to crustal faults: long-term fault slip rates
- Causes and effects of transient deformations: slow slip events and tectonic tremor
- Stress-mediated fault interactions and earthquake clustering: evaluation of mechanisms
- Structure and evolution of fault zones and systems: relation to earthquake physics
- Evolution of fault resistance during slip: scale-appropriate laws for rupture modeling
- Seismic wave generation and scattering: prediction of strong ground motions

Fault deformation modeling is multiscale on several levels

Multiscale Aspect I

Constitutive response of a finite-width shear zone of fault gouge surrounded by damaged bulk

Multiscale Aspect II

Spontaneous slip accumulation on a planar interface under slow loading assuming simple (elastic) bulk

10^9-10^{10} s slow loading / aseismic slip / slow deformation
10^5-10^6 s accelerating nucleation process
10 -100 s duration of a large inertially-controlled event
10^{-3}-10^{-1} s variation of stress and slip rate at rupture front

Multiscale Aspect III

Heterogeneous damaged temperature- and pressure-dependent visco- poro- elasto- plastic bulk material;

Locally non-planar shear zone with varying thickness.

Multiscale Aspect IV

Hierarchy of shear zones, interaction between them; large-scale fault system structure

⇒ **Need appropriate simulation methodologies, constitutive laws, and multiple physical inputs**

Simulation methodologies:
What we have (an incomplete list)

Fully elastodynamic codes for single dynamic rupture that incorporate several of the following: regional scale, off-fault plasticity or damage, temperature and pore pressure evolution, fault roughness, several fault segments. Limitations: Initial conditions that do not account for prior fault slip history; artificial nucleation process.

Fully elastodynamic models that reproduce long-term fault slip, including sequences of earthquakes and slow slip; include temperature and pore pressure evolution; based on BIM. Limitations: **Planar faults in homogeneous elastic bulk**.

Quasi-dynamic approaches that do not incorporate seismic waves but can afford more realistic parameter choices.

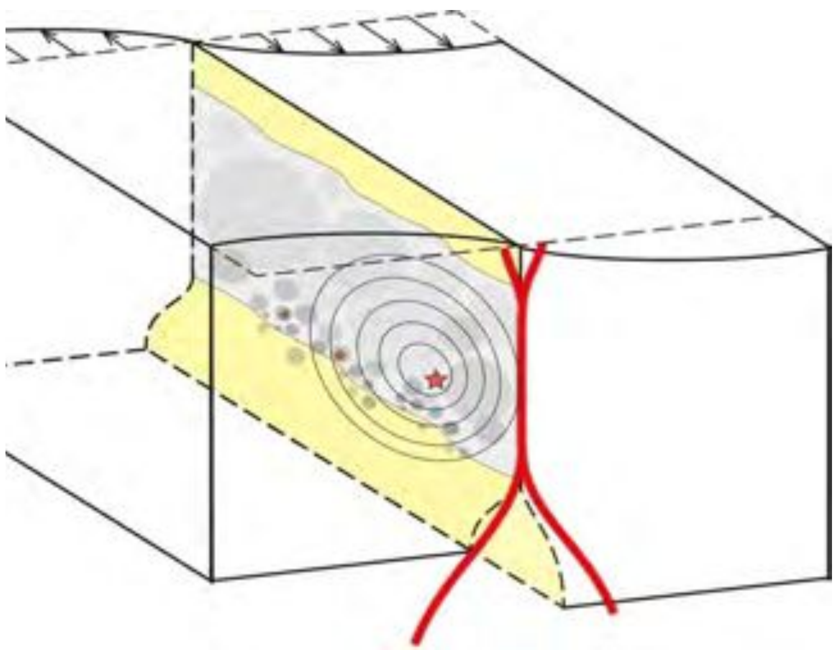
Approaches that switch between quasi-static and fully dynamic solvers to simulate long-term fault slip with earthquakes: being developed for non-planar faults in heterogeneous and nonelastic bulk. Limitations: Tractability.

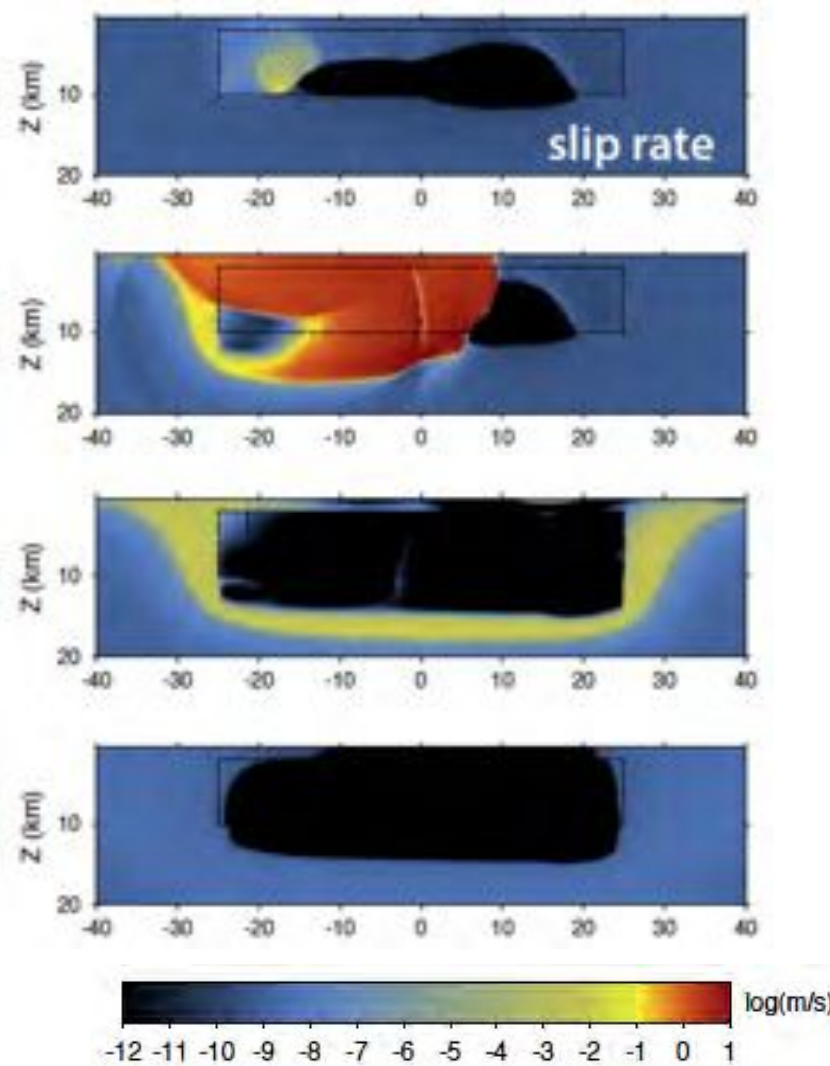
Semi-kinematic long-term simulations of seismicity on a network of faults in an elastic bulk: regional scale, back-slip loading, static elastic stress interactions. In RSQSim: rate and state friction, fluid effects can be incorporated through imposed changes in effective stress. Limitations: Approximate solution for slip based in simplified rules, no dynamic wave effects, only elastic, no easy way to add far-field loading, coarse mesh (resolves ruptures > M 6).

Quasi-static simulations of long-term deformation of viscoelastic bulk with various rheologies.

Long-term history of slip on a single planar fault in uniform elastic medium

3D rate-and-state model of a planar fault with temperature and pore pressure evolution due to shear heating



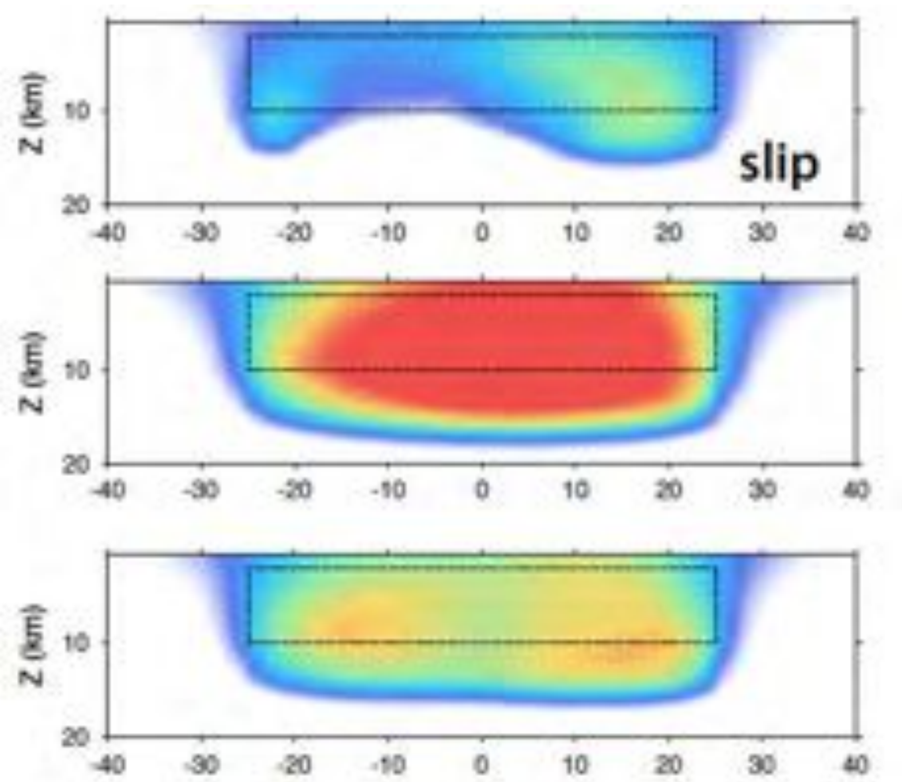


All stages of fault slip are resolved: nucleation, dynamic rupture, postseismic and interseseismic slow slip

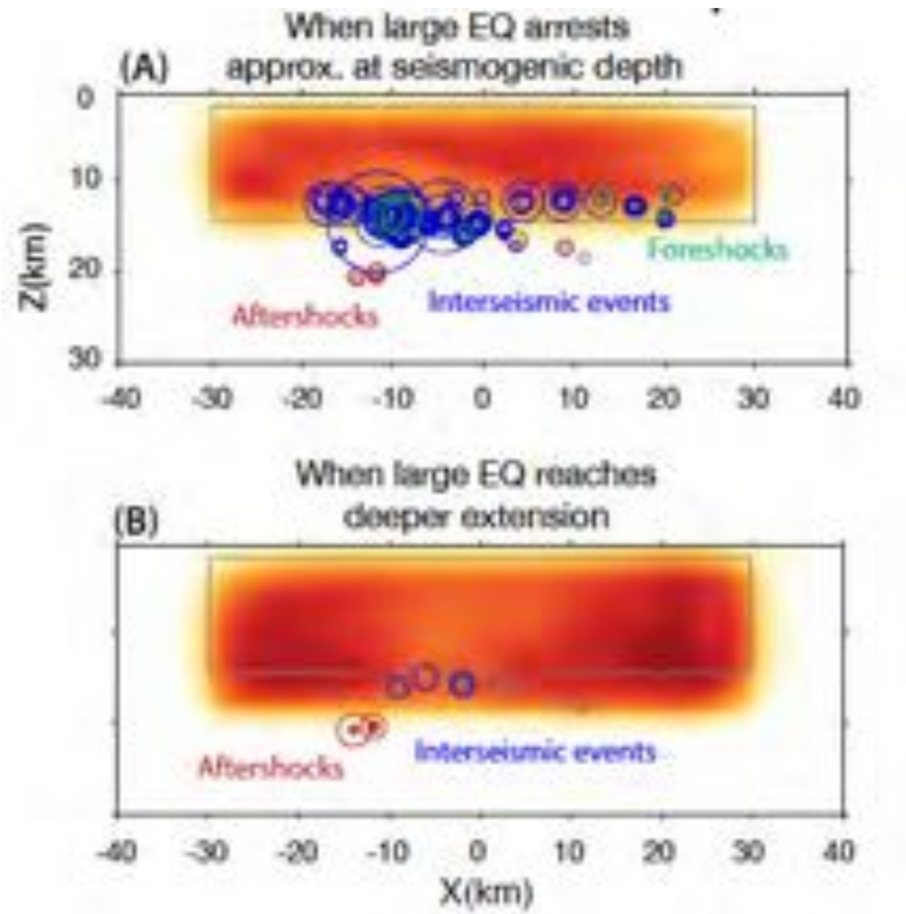
(Jiang and Lapusta, poster)

Long-term history of slip on a single planar fault in uniform elastic medium

Variability in final slip of large events



Microseismicity patterns at the bottom of the seismogenic zone depend on slip depth of large events

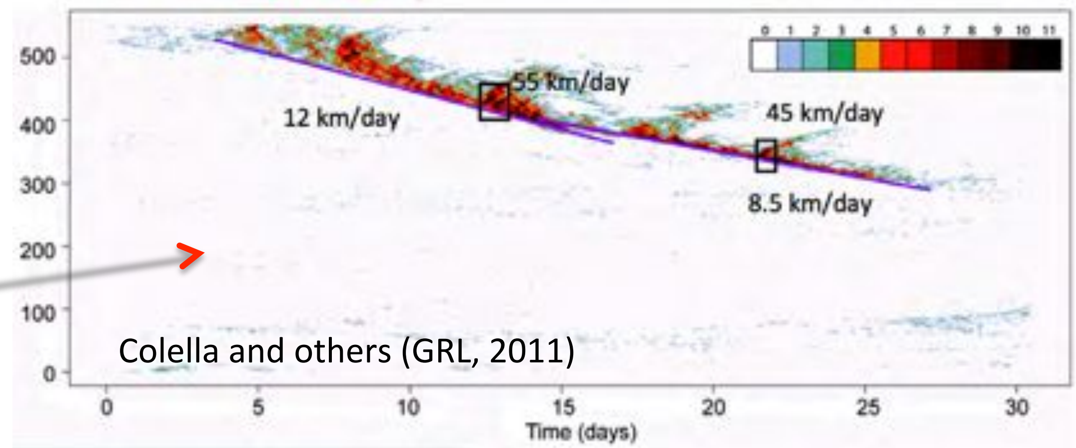


(Jiang and Lapusta, poster)

RSQSim – Capabilities

Slip phenomena

- Earthquakes
- Continuous creep
- Afterslip
- Slow slip events



Colella and others (GRL, 2011)

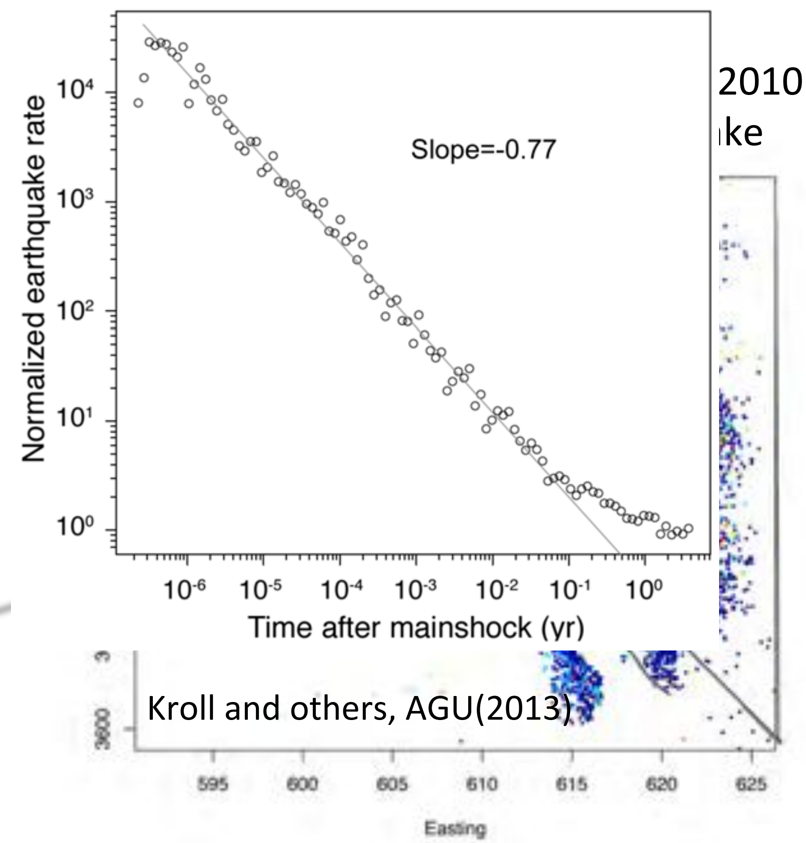
Long simulations of > 10^6 earthquakes

Rate- and state-dependent friction

- Foreshocks and aftershocks with Omori decay

Geometrically complex fault systems

- Triangular elements – complex surfaces
- All-California fault model with $1km^2$ elements

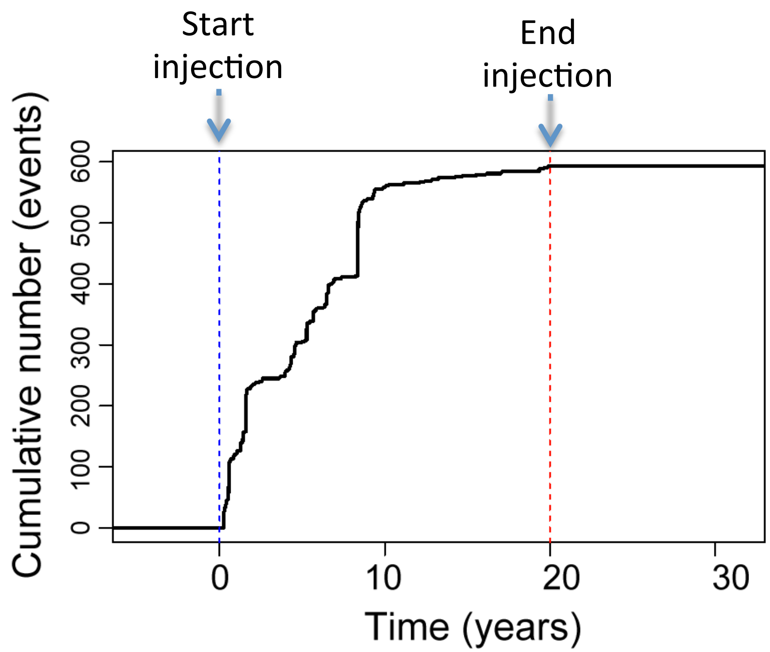


Kroll and others, AGU(2013)

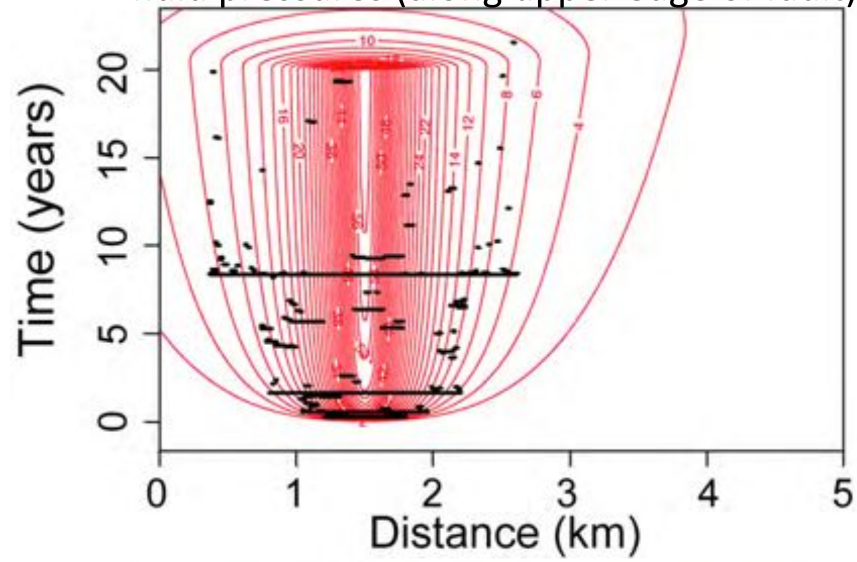
Seismicity off of explicitly modeled faults with rate-state equations

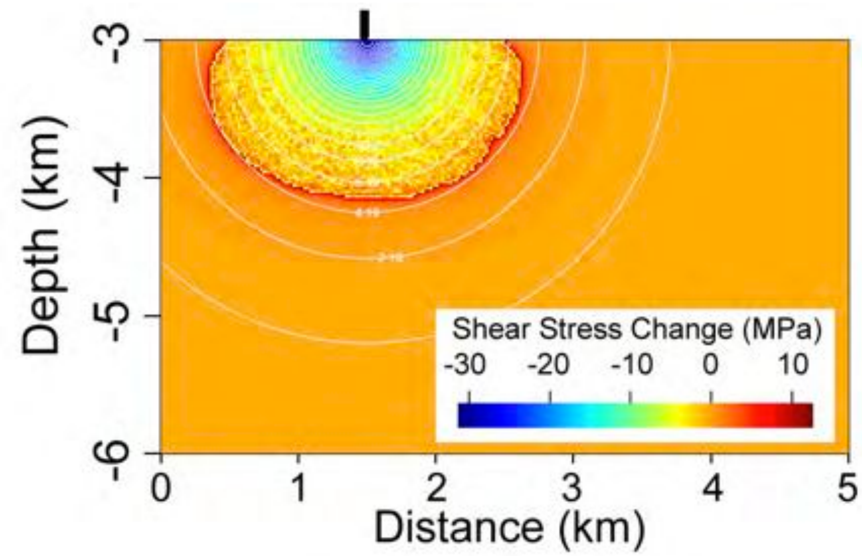
(Jim Dieterich and co-workers)

RSQSim – Simulations of induced seismicity by fluid injection



Space-time plot of earthquake ruptures and fluid pressures (along upper edge of fault)





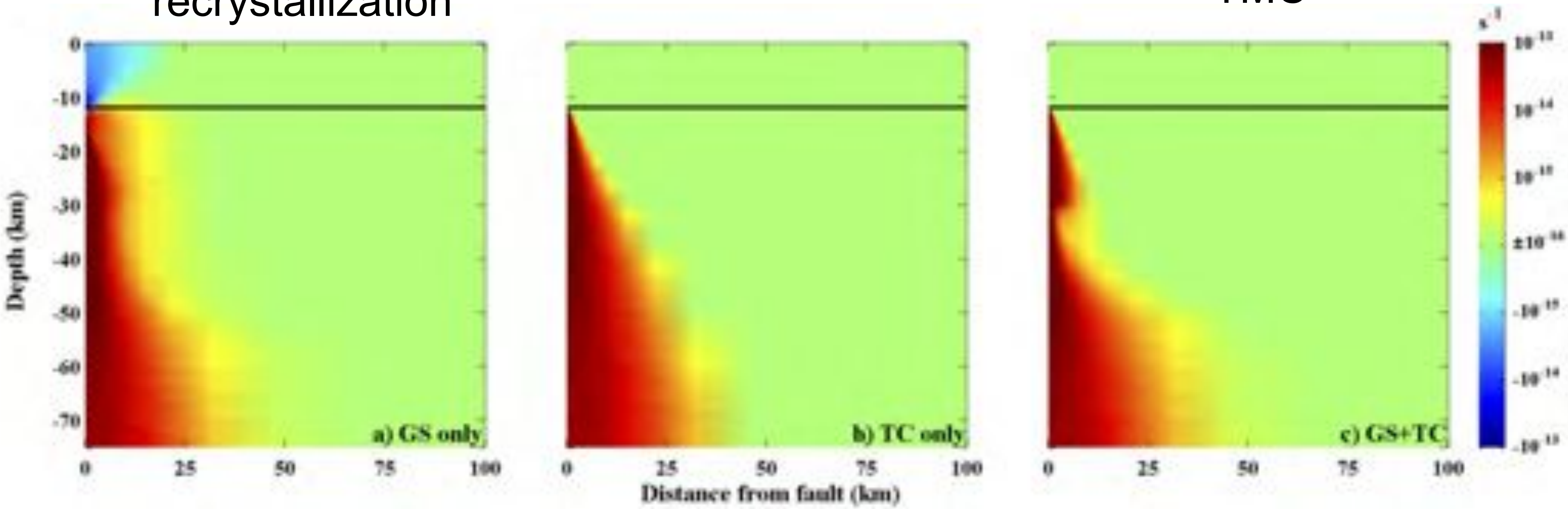
(Kroll, Dieterich, Richards-Dinger, poster)

Strain localization in a ductile substrate

Dynamic recrystallization

TMC

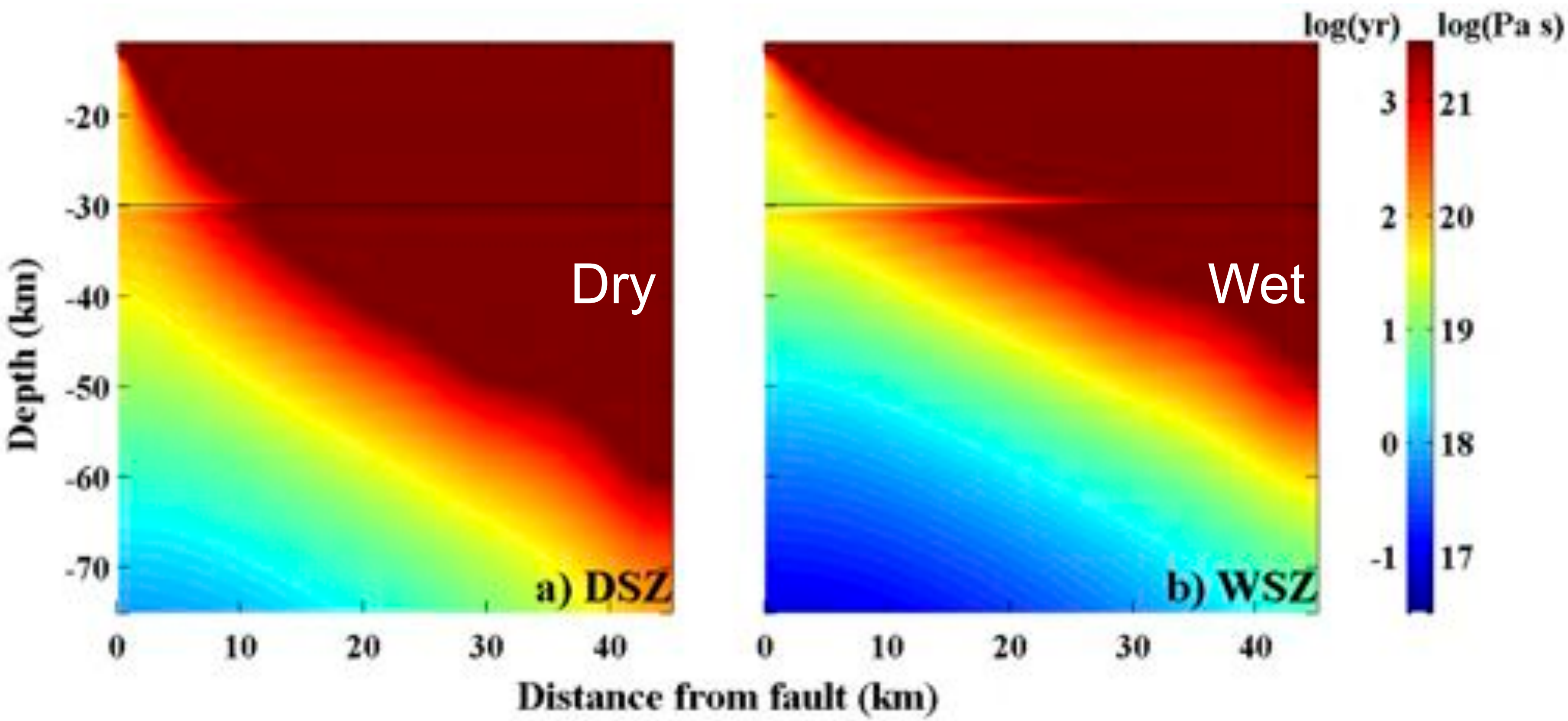
Dynamic recrystallization + TMC



strain rate

Takeuchi and Fialko, 2013

Effective viscosity after 20 Myr spin-up



$$\eta_{eff} = \frac{\sigma}{2\dot{\varepsilon}}$$

Takeuchi and Fialko, 2013

Simulation methodologies:
What do we want/need to develop in SCEC5?

What kind of problems would we like to address?

How do we develop scientific approaches for verification and validation of system-level earthquake modes acceptable to the broad community?

Input from:

Eric Dunham, Brad Aagaard, Pablo Ampuero, Jim Dieterich, Ruth Harris, Yuri Fialko, James Rice, Paul Segall, Terry Tullis

Problems to address with simulators in SCEC5

- Simulations of large dynamic events and ground shaking that are based on region-specific stress conditions
- Probability of ruptures jumping between rupture segments or being smaller than a rupture segment
- Potential for large ruptures or strain accumulation off known faults under conditions of realistic regional loading consistent with GPS/InSAR
- Effect of fluids on natural and induced earthquakes

All of these problems:

- Could relate to Community Stress Model or its further development;
- Require integration of observations/modeling that only SCEC could provide;
- Motivate development of simulators that:
  - Combine long-term simulations, dynamic wave effects, complex fault geometries, and realistic on- and off-fault properties;
  - Extend long-term seismicity simulations beyond elasticity, with realistic bulk rheologies and loading;
  - Couple fault deformation with fluid motion and effects.

Simulation methodologies: What do we want/need to develop in SCEC5?

What kind of problems would we like to address?

How do we develop scientific approaches for verification and validation of system-level earthquake models acceptable to the broad community?

- As more long-term simulators are developed that are trying to reproduce the same physics (nucleation and slip due to rate and state friction, evolution of fluid pressure etc), we can set up detailed comparisons between their results are currently done for dynamic rupture simulations: their handling of slow slip, accelerating slip (nucleation), problems with simple seismicity patterns etc.
- California-scale simulations need to be pushed down to M 3 (currently they are at ~ M 6) to allow for comparison with naturally occurring earthquake patterns.

Additional thoughts

- Relations between the overall slip and stress histories at each fault location may be affected by decomposion reactions and hence not expressible directly as a constitutive equation (FARM-related).
- Detailed simulations of single faults need to be continued, e.g., 2D simulations of dynamic ruptures with fault roughness and off-fault plasticity/damage need to be extended to 3D, to consider questions such as the origin of high-frequency ground motion (ground motion simulations).

Simulation methodologies: What we have (an incomplete list)

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Quasi-static simulations of long-term deformation of viscoelastic bulk with various rheologies.

Simulators in SCEC5

Problems to address

- Large dynamic events and ground shaking based on region-specific stress conditions
- Probability of ruptures being smaller/larger (jumping) than a rupture segment
- Potential for large ruptures or strain accumulation off known faults
- Effect of fluids on natural and induced earthquakes

Scientific approaches for verification and validation of system-level earthquake models

- Detailed comparisons between simulators that reproduce established fault physics on slow slip, accelerating slip (nucleation), problems with simple seismicity patterns etc.
- Comparison between regional sims and natural seismicity patterns down to M 3.

Simulator development

- Combine long-term simulations, dynamic wave effects, complex fault geometries, and realistic on- and off-fault properties;
- Extend long-term simulations beyond elasticity, with realistic bulk rheology and loading;
- Couple fault deformation with fluid motion and effects;
- Aim to extend both existing detailed rupture/fault simulations to longer-term histories and larger scales (approaches that switch between fully-dynamic and quasi-dynamic stages) and existing system-wide models to more advanced features and realistic loading.

Additional points

- Decomposition reaction and replacement of constitutive laws by systems of PDFs
- Further development of realistic simulations of single faults (e.g., roughness, damage etc).