Introduction: Advancing Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS)

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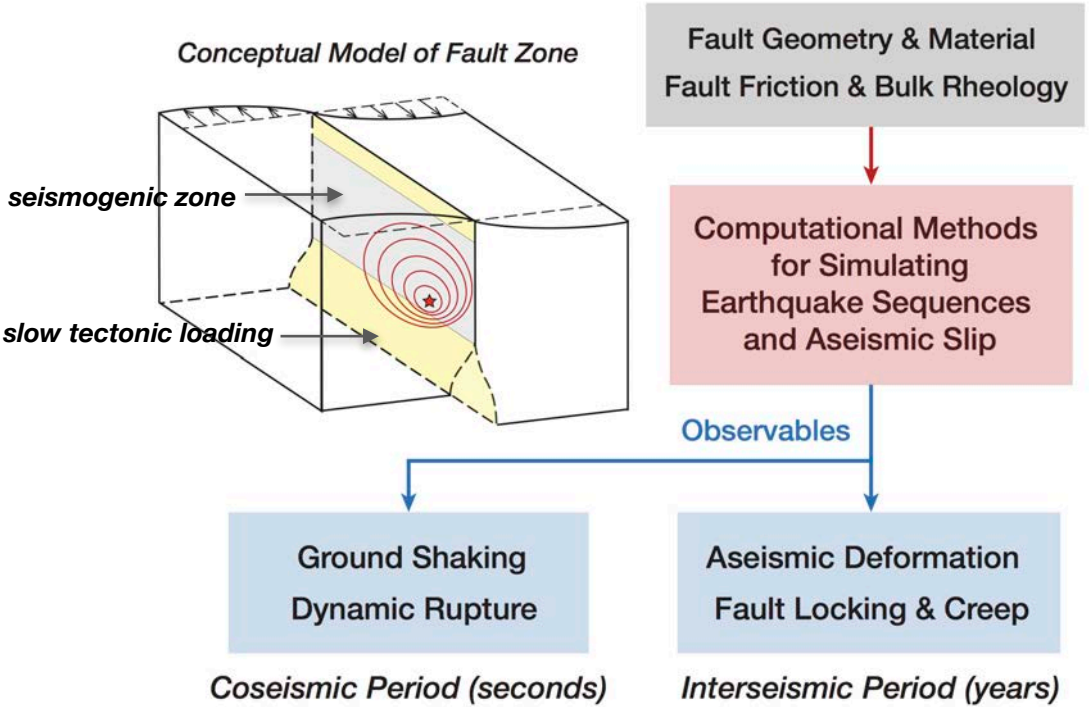
Outline

- Motivation
- Objectives
- Current activities
- Benchmarks for code verification
- Timeline for future activities
- Workshop agenda

Motivation

- SEAS (aka “seismic cycle”) simulations are now prevalent in earthquake research—addressing key SCEC objectives—but remain untested
- **Dynamic rupture (DR) group**
  - Simulating detailed single-event earthquake ruptures
  - Successful code verification exercises and ongoing validation efforts
  - Imposed artificial prestress conditions and ad hoc nucleation procedures
- **Earthquake Simulators (ES)**
  - Simulating millennium-scale seismicity patterns in fault systems
  - Quasi-static approximation and some key physical features missing
- A new generation of verified SEAS models is needed
  - Simulating longer periods of earthquake activity than single-event ruptures
  - Computational rigor and physically sound approaches

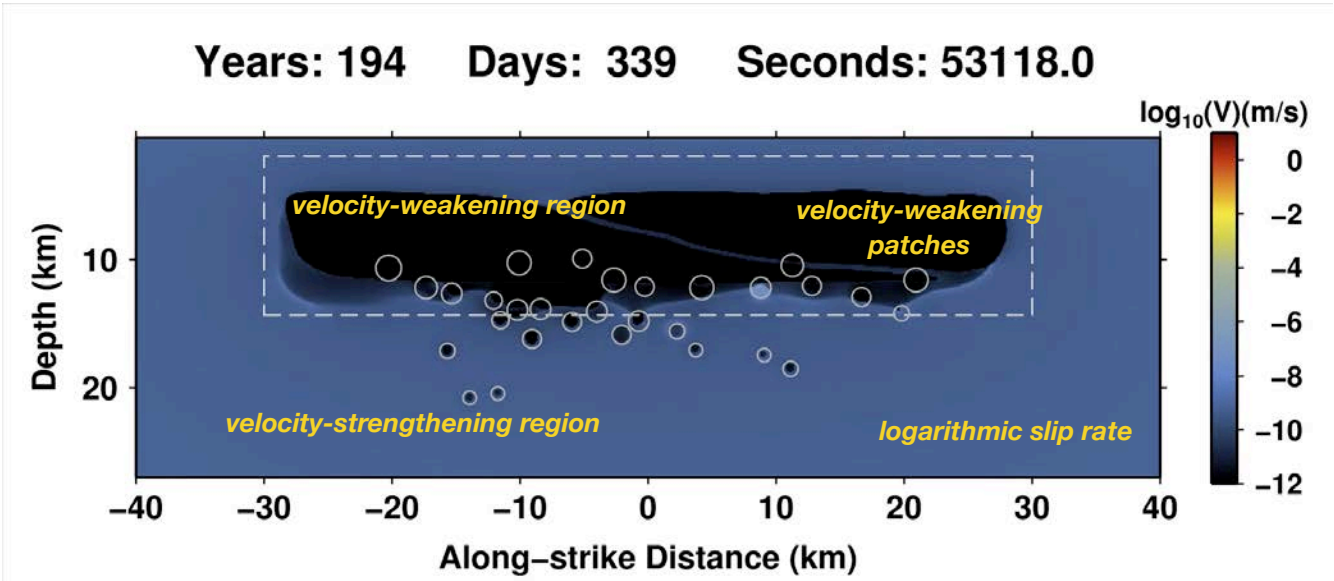
Ingredients & output of SEAS models



Problems that set SEAS models apart from DR

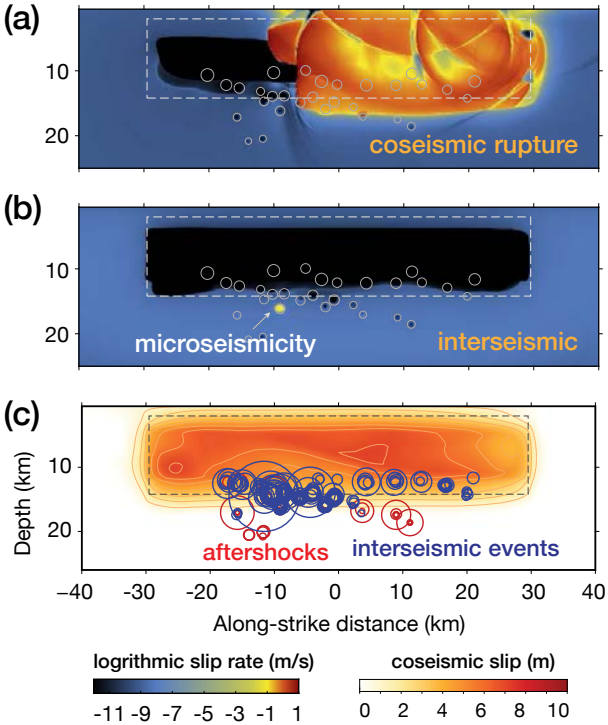
- The use of variable time stepping and possible switching between different computational schemes to capture inter- and co-seismic phases.
- The interaction between nonlinear nature of the problem and accumulation of roundoff errors.
- The need to distinguish between legitimate solution differences and those due to improper choices of algorithm, model resolution, and modeling procedures.
- The importance of numerical efficiency and computational performance for feasibility of even the most basic problems.

Examples of SEAS modeling



A planar fault in a 3D homogenous half-space

Jiang and Lapusta, Science, 2016



Complex interactions between earthquakes and aseismic slip

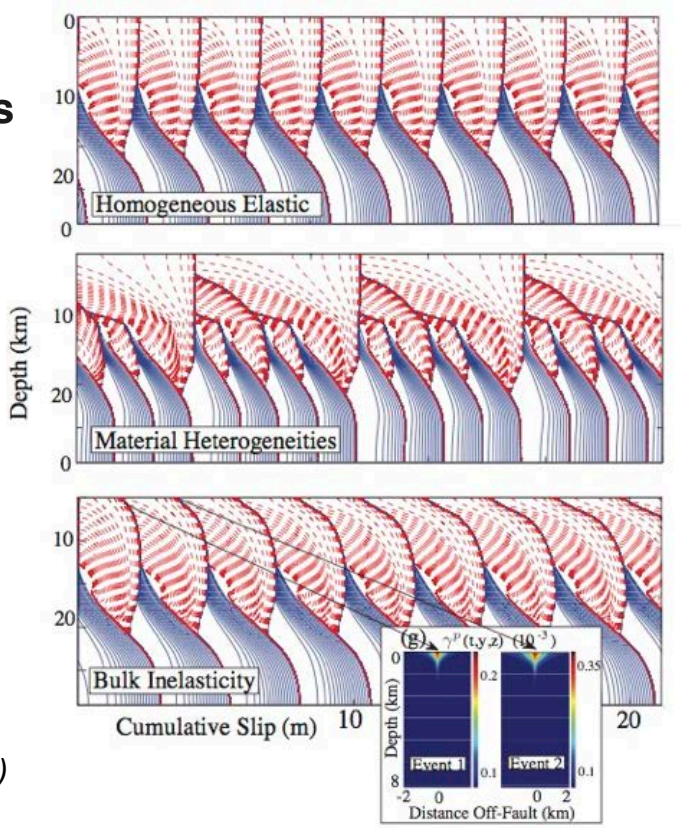
- Fully dynamic rupture
- Postseismic stress relaxation
- Microseismicity
- Complexity in large events
- Interseismic fault coupling
- Compare with seismological, geodetic, and geological data

Jiang and Lapusta (Science, 2016; JGR, 2017)

How rheology and structure influence earthquake sequences

- Quasi-dynamic earthquake ruptures in 2D antiplane models
- Heterogeneous bulk material properties
- Off-fault plasticity

cumulative fault slip along depth



Erickson and Dunham (JGR, 2014)
Erickson et al. (JMPS, 2017)

Complexities in SEAS problems

- Transition from slow, quasi-static to dynamic, wave-producing slip
- Stress transfer due to dynamic waves
- Transition to postseismic slip
- Postseismic and interseismic slip and the associated stress redistribution
- Interaction with the deep visco-elasto-plastic response and the associated stress redistribution
- Interaction with fluids throughout the cycle
- Interaction with off-fault damage and healing
- The role of geometrical complexities

Investigated in a number of studies *(e.g., Jiang and Lapusta, 2016; Erickson and Dunham, 2014; Luo and Ampuero, 2011; Barbot et al., 2012; Liu, 2013; Wei, 2013; Segall and Bradley, 2012; Kaneko et al., 2011; van Dinther et al., 2013; Hajarolasvadi and Elbanna, 2017; Kroll et al., 2017; Tal et al., 2018)*

Some outstanding questions

- How do these physical factors influence the earthquake cycle? Do they matter? How to implement them with efficiency in 3D, larger scale simulations (e.g., Earthquake Simulators at SCEC)?
- Do our numerical models resolve the “true” fault behavior and its complexity? What features in models may arise from numerical approximation and resolution issues?
- What are the best practices and significant issues for SEAS modeling?

Objectives of SEAS working group

- Lead the efforts on code verification of SEAS models
- Explore important issues in SEAS modeling and further advance our computational capabilities
- Promote robust and reproducible earthquake science
- Lend experience and tools to the community
- Provide synergy with other SCEC working groups such as the Dynamic Rupture group, Earthquake Simulators, Community Rheology Model, etc

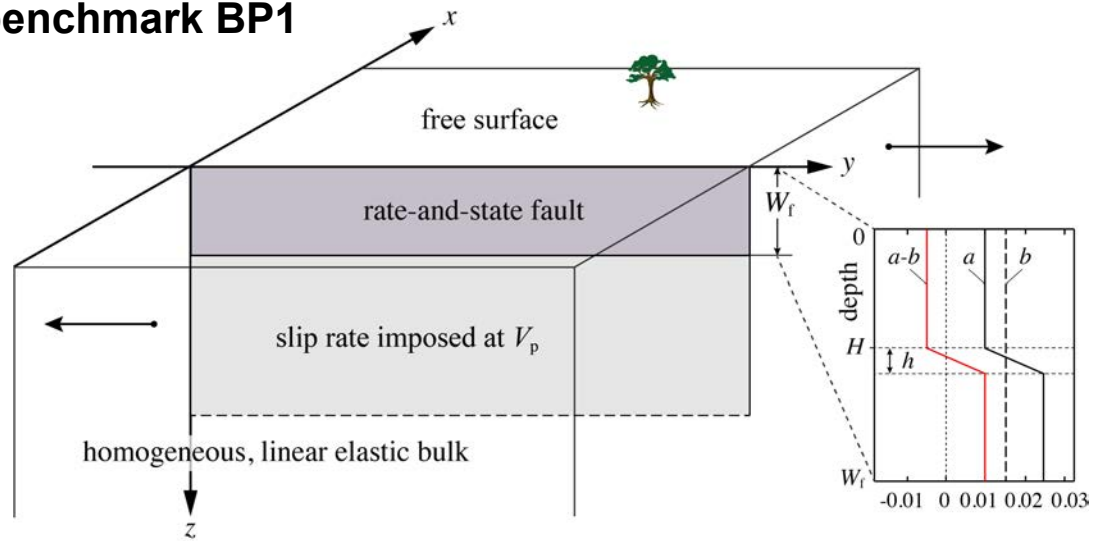
Past & current activities

- Submitted SCEC proposals for working group and workshop (Nov.)
- Developed the first Benchmark Problem BP1 (Mar.)
- Established online platform with basic model comparison tools (Mar.)
- Received and analyzed 23 submissions from 11 modelers
- The current workshop for science talks, benchmark results, & discussions

Benchmarks for code verification

- Guidelines
  - Start simple & incrementally increase model complexity
  - Take advantage of experience and tools from the dynamic rupture group
  - Design benchmarks that maximize participations
  - Develop the web platform based on comparison needs
- Tasks
  - What model features should we compare?
  - How do we assess agreements and discrepancies?
  - What constitute successful code verifications for SEAS models?

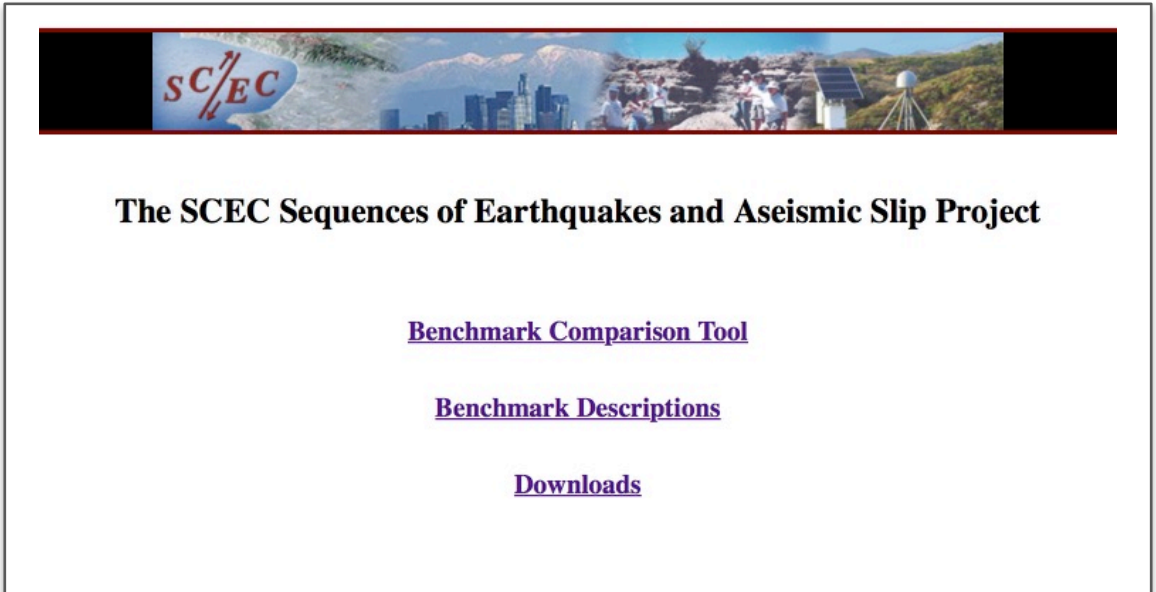
1st benchmark BP1



2D anti-plane shear motion. The fault is a vertical strike-slip fault in a homogeneous half-space. Friction is regularized rate-and-state friction with the aging law. (readily adaptable to a 3D benchmark)

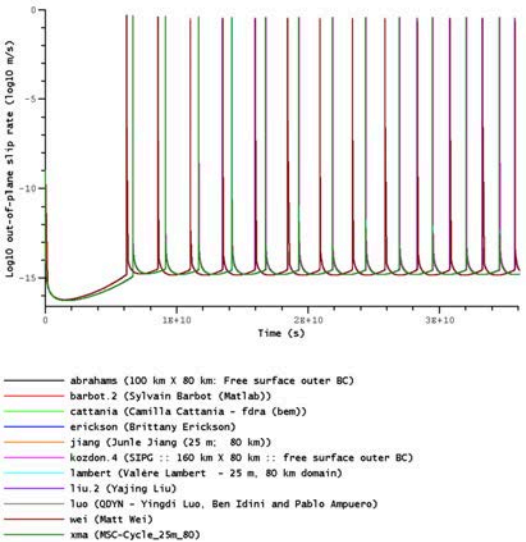
Online platform

- Code verification web server installed and maintained by Michael Barall (http://scecdata.usc.edu/cvws/seas/index.html)
- Using existing architecture/tools from dynamic rupture group



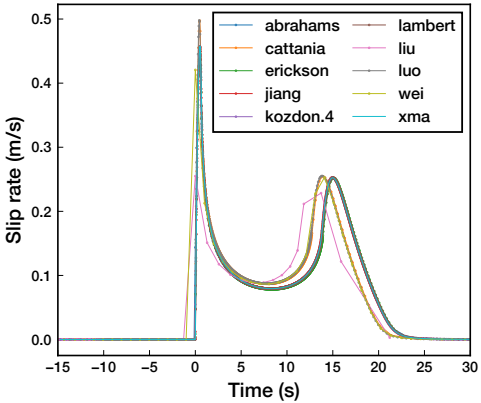
Benchmark results

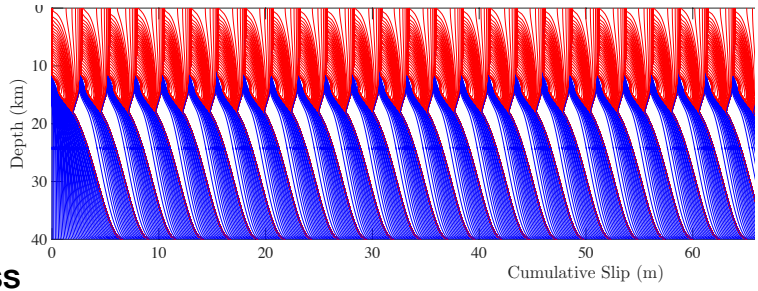
11 models and 23 model submissions



long-term evolution of slip/rate/stress (online platform)

coseismic processes (manual)





Slip evolution along depth (manual)

Benchmark design

- Ingredients in benchmark design
  - 2D anti-plane/in-plane or 3D problems
  - State evolution in friction laws (aging vs. slip formulations)
  - Complexity in structure, geometry, or frictional properties
  - Fluid processes, inelastic effects, etc.
- The next benchmark(s)
  - 3D problem similar to BP1 (with a lower resolution)
  - 2D problem with viscoelasticity
  - 2D problem with different evolution laws
- Future benchmarks?

Timelines for future activities

- Proposals for 2018
  - SEAS verification exercises in SCEC5: Pending
    - Co-PIs: Erickson, Jiang, and Barall
    - Other modelers to request separate funding from SCEC or others
  - One-day SEAS-themed workshop (2019 Spring): Pending
- Conference presentations
  - 2018 SCEC and AGU annual meetings, and others.
- Group meetings
  - 2018 SCEC meeting and potential 2019 workshop
- Publications
  - Development of an initial set of 2D/3D benchmarks and significant SEAS issues

Workshop agenda

Monday afternoon:
SEAS modeling and its connections to dynamic rupture problems

14:30 - 15:00	Introduction to SEAS activities	*Brittany Erickson / Junle Jiang*
15:00 - 15:15	SEAS: on resolution, complexity, and dynamic effects	*Nadia Lapusta*
15:15 - 15:30	Modeling of the nucleation process of laboratory and crustal earthquakes	*Yoshihiro Kaneko*
15:30 - 15:45	Coupling spectral boundary integral and volume-based models for high resolution fault zone physics	*Ahmed Elbanna*
15:45 - 16:00	Modeling the rupture process on rough faults during multiple slip events wit hte mortar finite element method	*Yuval Tal*
16:00 - 16:15	*Break*	
16:15 - 16:30	Discontinuous Galerkin methods for earthquake cycle simulations	*Jeremy Kozdon*
16:30 - 16:45	RSQSim modeling and applications	*Kayla Kroll*
16:45 - 17:30	Discussions	

Tuesday morning:

Multi-physics and diverse observables in SEAS models

08:30 - 08:45	The effect of shear heating on the earthquake cycle	*Kali Allison*
08:45 - 09:00	Time stepping for earthquake cycles with plasticity	*Brittany Erickson*
09:00 - 09:15	Modelling frictional faults as plastic shear bands in nonlinear media	*Casper Pranger*
09:15 - 09:30	FDRA - Fault dynamics with radition damping approximation: history and capabilities	*Paul Segall*
09:30 - 09:45	The spectrum of rupture styles at subduction zone governed by the geometry and rheology of the upper plate	*Sylvain Barbot*
09:45 - 10:00	Modeling of slow slip events on a non-planar subduction fault	*Yajing Liu*
10:00 - 10:15	Numerical simulation of dynamic triggering of slow slip events in California and New Zealand	*Matt Wei*
10:15 - 10:30	Break	
10:30 - 12:00	Benchmark results and discussions	*Brittany Erickson* / *Junle Jiang*
12:00 - 13:00	Lunch	
13:00 - 14:30	Workshop wrap-up and future plans	*Brittany Erickson* / *Junle Jiang*