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

Junle Jiang (Cornell University)

Brittany Erickson (Portland State University)

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SCEC an NSF + USGS center

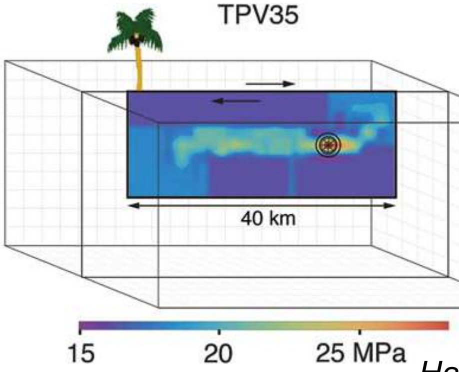
Overview

- Introduction and motivation
- Early results and achievements
- Next steps and future directions

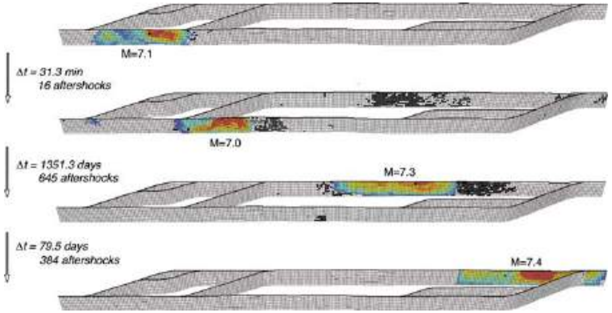
Introduction & Motivation

- Comparisons of earthquake models
- Applications and challenges of SEAS models
- The SEAS initiative at SCEC

Approaches to modeling earthquakes



Harris et al., 2018



Dieterich and Richards-Dinger, 2010

Spontaneous dynamic ruptures

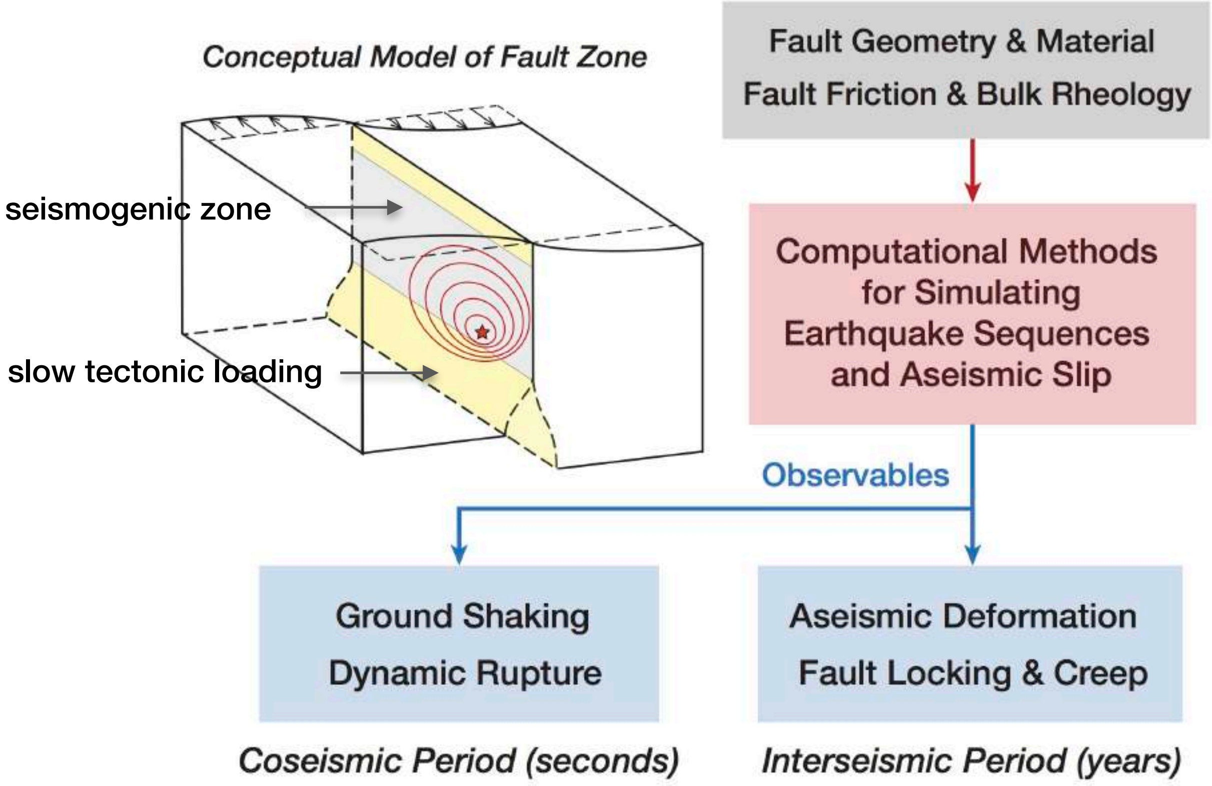
- Detailed single-event earthquake ruptures
- Successful code verification exercises and ongoing validation efforts
- Imposed artificial prestress conditions and ad hoc nucleation procedures

Earthquake Simulators

- Able to simulate millennium-scale seismicity patterns in fault systems
- Quasi-static approximation and simplification of interseismic loading to allow numerical tractability

What are SEAS models?

Sequences of Earthquakes and Aseismic Slip



Input

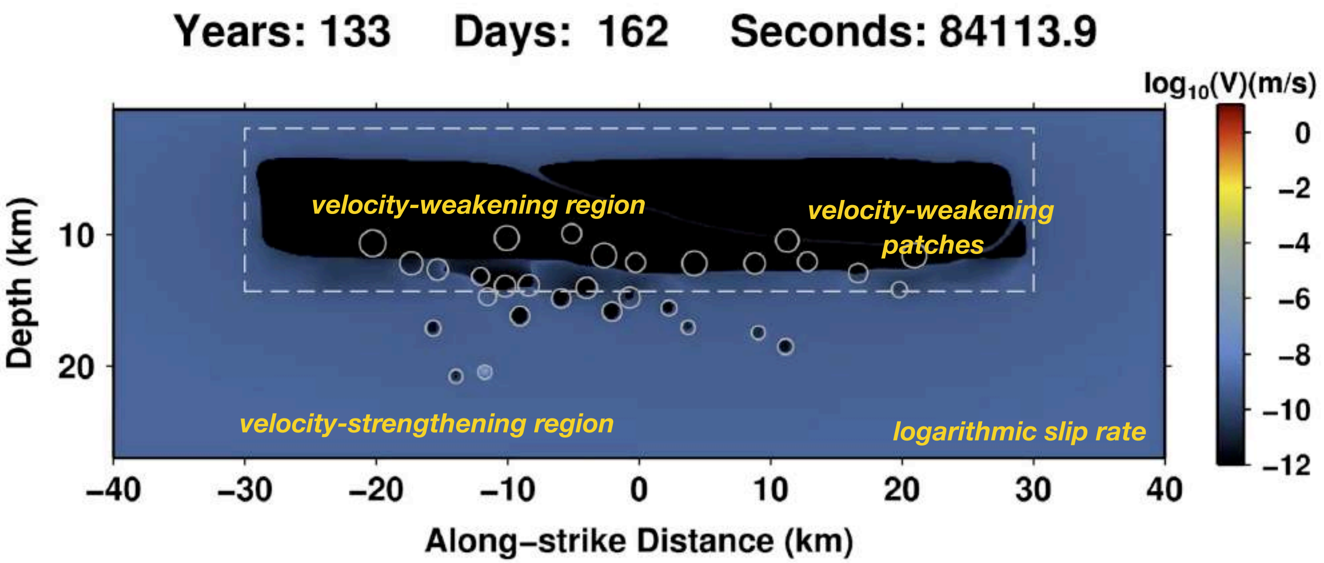
Distinct features:

(1) Interactions between earthquakes and aseismic slip

(2) Capture detailed earthquake rupture process

Examples of SEAS models

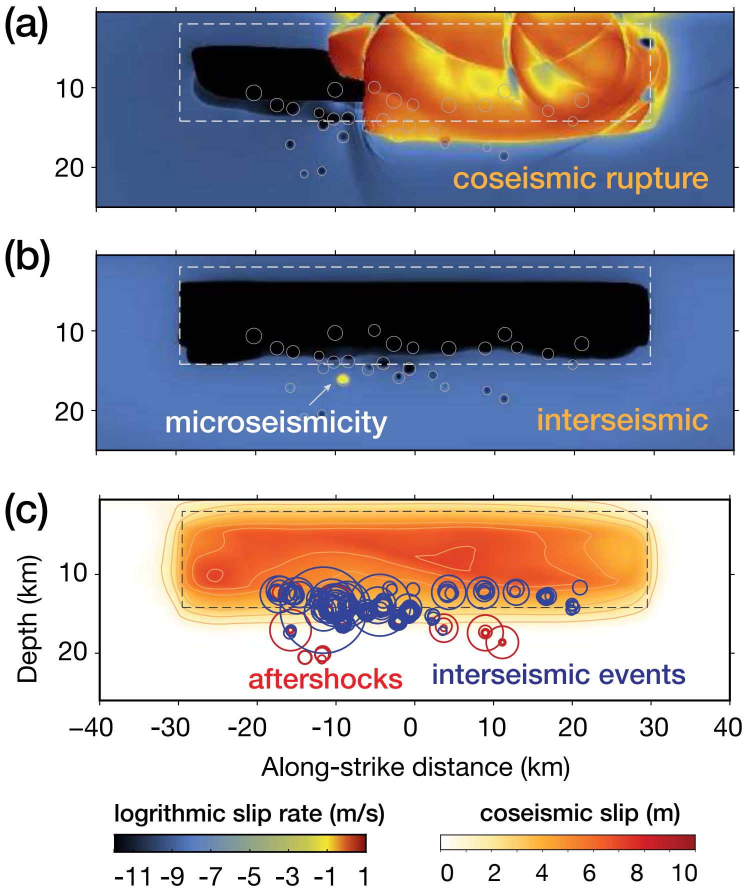
Interplay between dynamic earthquakes
and fault creep on a fault plane



Jiang and Lapusta, Science, 2016

Interactions between fault creep, small and large events

- 3D models with a homogenous media
- Fully dynamic rupture
- Postseismic stress relaxation
- Microseismicity
- Interseismic fault coupling
- Compare with seismological, geodetic, and geological data

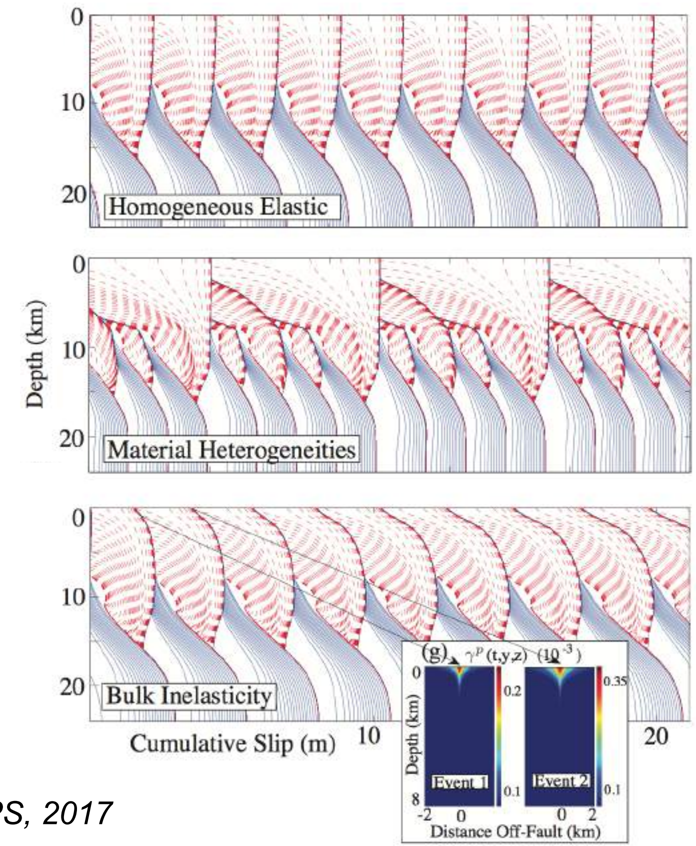


Jiang and Lapusta, Science, 2016; JGR, 2017

How rheology or structure influences earthquake patterns

- 2D antiplane models
- Quasi-dynamic earthquake ruptures
- Heterogeneous bulk material properties
- Off-fault plasticity
- Can further incorporate other inelastic rheology and fluid processes

cumulative fault slip along depth



Erickson and Dunham, JGR, 2014; Erickson et al., JMPS, 2017

Capability and complexity of SEAS models

- Transition from slow, quasi-static deformation to dynamic, wave-producing slip and to postseismic and interseismic deformation
- Interactions between seismicity and aseismic transients

multiple time and space scales

- Interactions with the deeper inelastic response, fluids, and off-fault damage and healing
- Geometrical complexities and fault heterogeneity

multiple physical factors

SEAS ("seismic cycle") models are now prevalent in earthquake research—addressing key SCEC objectives—but remain untested

Outstanding questions

- Do our numerical models resolve the “true” fault behavior and its complexity?
- What model features may arise from numerical approximation and resolution issues?
- How do these physical factors influence the earthquake cycle? Do they matter?
- How to implement them with efficiency in 3D, larger scale simulations?

Verifying different computational codes is the first critical step

Community efforts are needed to address these issues

Objectives for the SEAS initiative at SCEC5

- Lead the efforts on verification of SEAS models
- Explore important issues in SEAS modeling
- Further advance our computational capabilities

community benchmark exercises

discussions/workshop

presentation/publication

- Promote robust and reproducible earthquake science
- Share experience and tools within the community (including SCEC working groups, e.g., Dynamic Rupture group, Earthquake Simulators, Community Rheology Model)

Early Results & Achievements

collaboration, workshop & benchmark

What we have accomplished

- Initiated a SEAS working group (10+ modeling groups; 40+ ppl on our email list)
- Developed our first SEAS benchmark problem in March
- Established an online platform for SEAS model comparison
- A SCEC workshop on April 23-24
    - Jointly held with the dynamic rupture code validation group
    - 60 Participants (online & remote) from 7 countries, half students & postdocs
    - Talks on science & codes, benchmark results & discussions

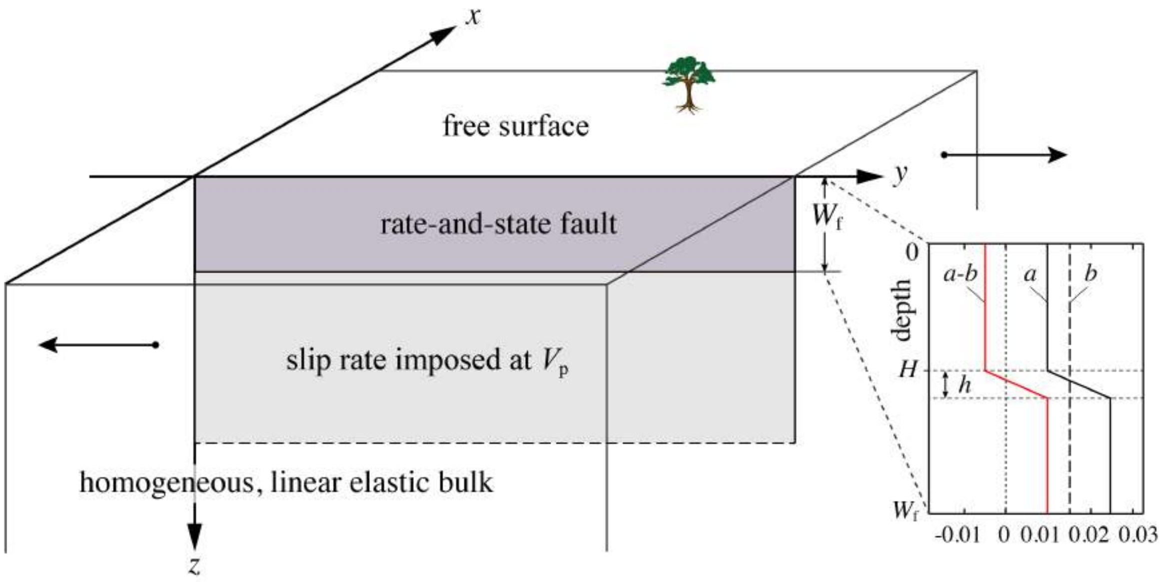
Check out our SCEC poster (#192):

Erickson, Jiang, Barall, Lapusta, Dunham, Harris, Abrahams, Allison, Ampuero, Barbot, Cattania, Elbanna, Fialko, Idini Zabala, Kozdon, Lambert, Liu, Luo, Ma, Segall, Shi, & Wei, The Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS): Initial Benchmarks and Future Directions.

Design benchmarks for code verification

- Guidelines
  - Start simple & incrementally increase model complexity
  - Draw collaboration experience from SCEC community, especially the dynamic rupture group
  - Building the community platform based on existing SCEC resource and our needs
  - Design benchmarks that maximize participations
- 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



based on Rice, 1993

- 2D anti-plane problem
- 1D vertical strike-slip fault in a homogeneous half-space
- Rate-and-state friction with the aging evolution law
- Quasi-dynamic earthquakes
- Define a mathematical problem, leaving computational implementation up to modelers

Online platform

- Code verification web server maintained by Michael Barall
- Building on the existing platform of dynamic rupture group
- Facilitate submissions and analysis of 20+ models from 11 model groups for BP1

The SCEC Sequences of Earthquakes and Aseismic Slip Project

Benchmark Comparison Tool

Benchmark Descriptions

Downloads

http://scecdata.usc.edu/cvws/seas/index.html

Select Benchmark

Benchmarks

Name	Date	Description	Action
bp1	4/14/2018 8:08 AM	2D Antiplane Shear	Select

Select Modeler

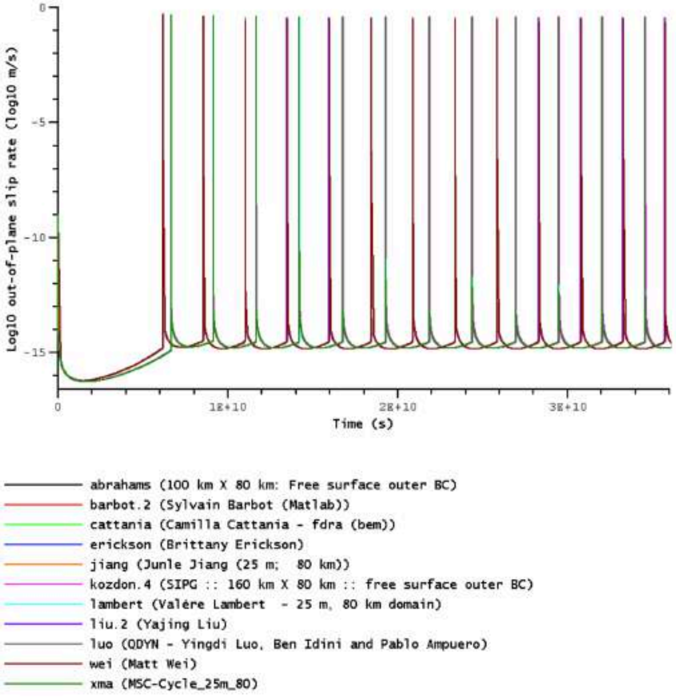
Users — Select Checked — Select All

	Name	Description	Action
☐	abrahams	100 km X 80 km: Free surface outer BC	Select
☐	abrahams.2	100 km X 80 km: Vp/2 outer BC	Select
☐	abrahams.3	400 km X 200 km: Vp/2 outer BC	Select
☐	barbot	Sylvain Barbot (Fortran90)	Select
☐	barbot.2	Sylvain Barbot (Matlab)	Select
☐	cattania	Camilla Cattania - fdra (bem)	Select
☐	cattania.2	Camilla Cattania - fdra (fft, 160 km)	Select
☐	cattania.3	Camilla Cattania - fdra (fft, 640 km)	Select

Benchmark exercises - how to compare models?

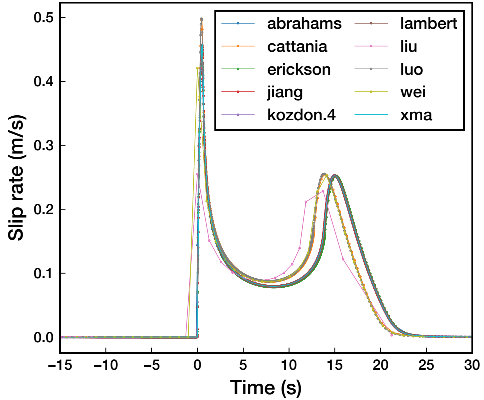
Utilizing current online tools

long-term evolution of slip/rate/stress

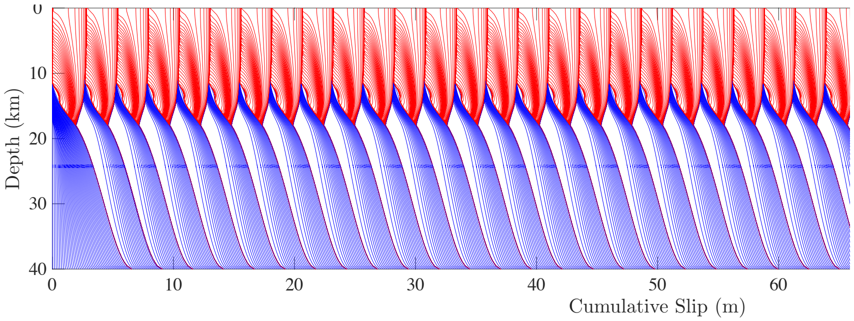


Explore other model features

coseismic evolution of slip rate and stress



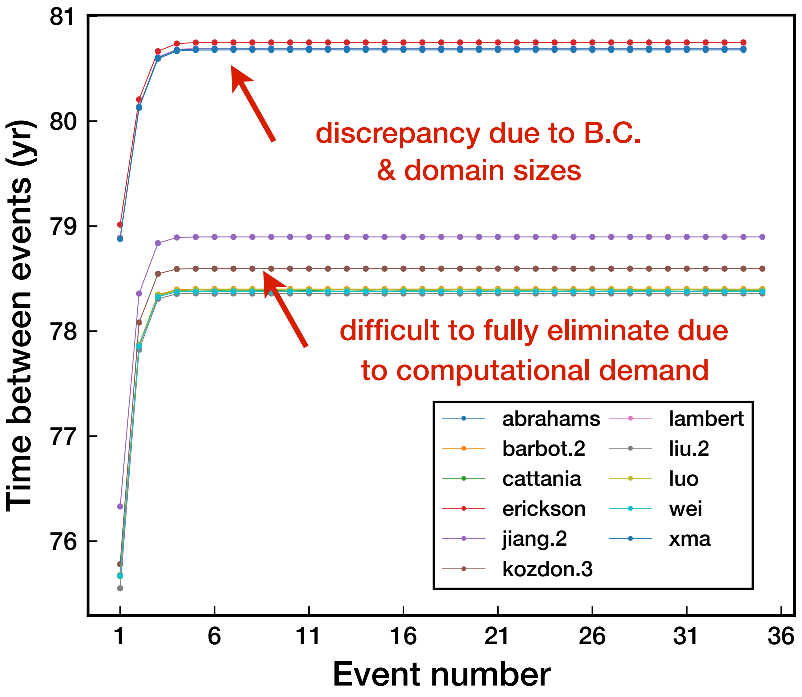
Slip evolution along depth



What constitute a successful benchmark?

- All models are qualitatively consistent
- Major quantitative discrepancies
  - exist in interseismic loading, prestress, and coseismic rupture speed
  - due to boundary conditions and computational domain sizes
- Minor discrepancies may be inevitable
  - due to volume vs. boundary methods and approximation of the half space
- Many models produce near-perfect match

earthquake recurrence times



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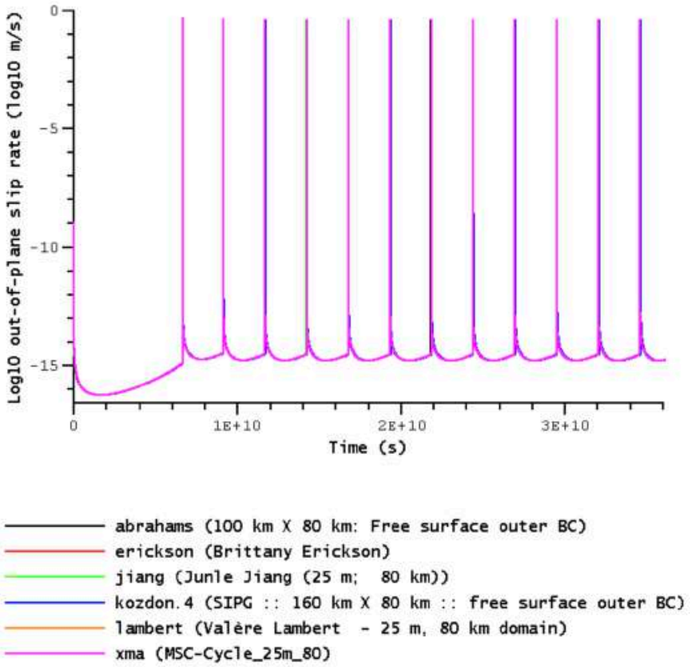
long-term slip rate evolution



Next Steps & Future Directions

What we want to achieve in SCEC5

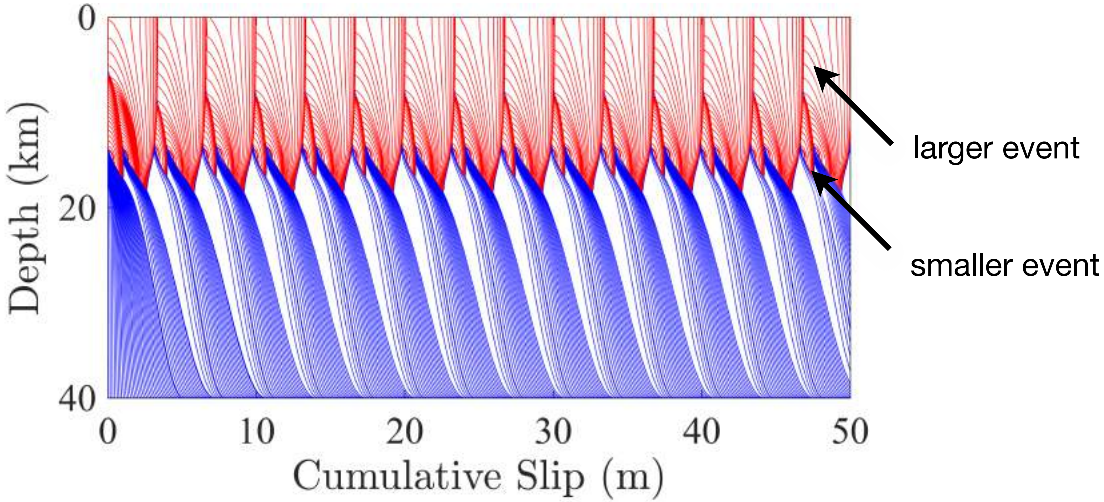
Towards model validation

Our Goals in SCEC5

- Achieve successful community code verification exercises
    - Develop a suite of benchmarks and verification tools for use within the community
    - Establish best computational practices
    - Share results/lessons with the broader community
- Work towards validating SEAS models with real data
    - Verification is the first step - different models can accurately solve the problem
    - Validation is the ultimate goal - such models can capture “true” behavior of earthquakes and faults
    - Determine clear input/output from/to other SCEC working groups

Upcoming benchmarks

- BP2: 2D anti-plane quasi-dynamic problem with smaller nucleation size (2018 Fall)
    - Microseismicity at the bottom of the seismogenic zone
    - Understand event size variability due to physics or numerical procedures



Upcoming benchmarks

- BP2: 2D anti-plane quasi-dynamic problem with smaller nucleation size (2018 Fall)
  - Microseismicity at the bottom of the seismogenic zone
  - Understand event complexity due to physics or numerical procedures
- BP3: 3D quasi-dynamic problem for BP1 (2019 Fall)
  - More realistic earthquake propagation
  - Computational demand and resolution issues
- BP4: 2D in-plane quasi-dynamic problem with a dipping fault (2019 Fall)
  - The role of fault geometry
  - Computational domain size and boundary conditions

Plan for future benchmarks

- **Coupling with inelastic processes and/or fluids**
  - Relevance to Community Rheology/Thermal/Geodetic Models, etc.
- **Fully-dynamic earthquake ruptures**
  - Further connection with Dynamic Rupture group, Ground Motion, etc.
- **Heterogeneous frictional properties and event complexity**
  - Further connection with Earthquake Simulators

Opportunities to promote a new generation of more advanced SEAS models

Towards model validation with observations

- **Use lab/field data to bear on the design/input/output of SEAS models**
  - *Rock mechanics*: friction laws, bulk rheology, …
  - *Tectonic geodesy*: co-/post-/inter-seismic deformation, aseismic transient, …
  - *Seismology*: velocity structure, microseismicity, ground motion, …
  - *Earthquake geology*: paleoseismic record, fault geometry, …
- **Explore specific cases with broad implications**
  - Variable recurrence intervals of the Parkfield sequence
  - Variable earthquake sizes on the Imperial fault
  - What controls rupture termination - Earthquake Gates Initiative
- **Advantages of group efforts**
  - Ensemble study, model variability/uncertainty, etc

Thanks!

Check out our SCEC poster (#192):

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Contact us to join our email list (berickson@pdx.edu, jjiang@cornell.edu)