# Sequences of Earthquakes and Aseismic Slip (SEAS): From Community Code Verification to Cross-Scale Validation

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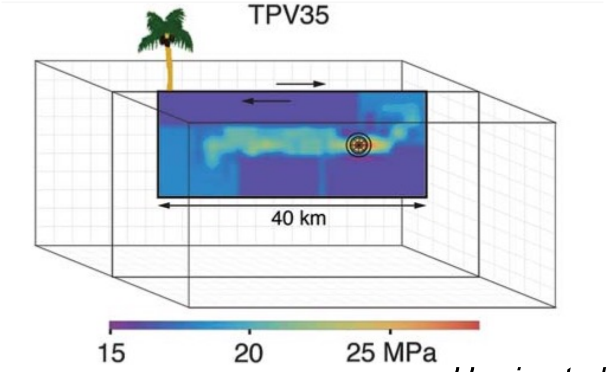
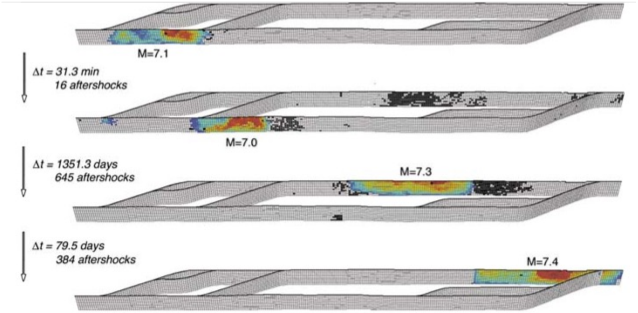
# Overview

- Background & History
- Benchmark Progression & Findings
- Toward Validation

# Approaches to modeling earthquakes




*Harris et al., 2018*




*Dieterich and Richards-Dinger, 2010*

## Spontaneous dynamic ruptures

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

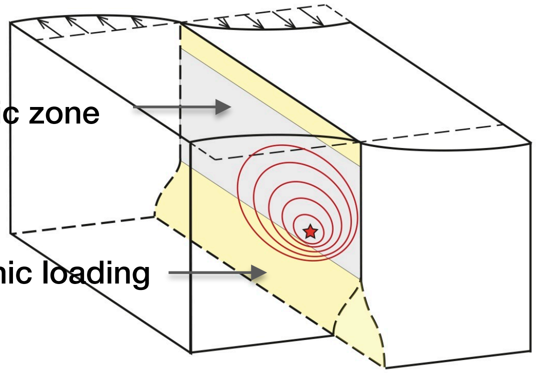
## Earthquake Simulators

- Able to simulate millennium-scale seismicity patterns in fault systems
- Quasi-static approximation and simplified aseismic loading to allow numerical tractability

# What are SEAS models?

**S**equences of **E**arthquakes and **A**seismic **S**lip

*Conceptual Model of Fault Zone*




Fault Geometry & Material
Fault Friction & Bulk Rheology

Input

Computational Methods for Simulating Earthquake Sequences and Aseismic Slip

Observables

Ground Shaking
Dynamic Rupture

*Coseismic Period (seconds)*

Aseismic Deformation
Fault Locking & Creep

*Interseismic Period (years)*

Distinct features:

(1) Interactions between earthquakes and aseismic slip

(2) Capture detailed earthquake rupture process

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

*multiple time and space scales*

*multiple physical factors*

SEAS ("seismic cycle") models are now prevalent in earthquake research

# 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**

# SEAS in SCEC4/5

- SEAS was initiated in 2018 by Brittany Erickson, Junle Jiang, and Michael Barall, with much guidance from Ruth Harris, Nadia Lapusta and Eric Dunham
- Developed first SEAS benchmark problem in March 2018
- Held 1st workshop with dynamic rupture group in April 2018
- Established an online platform for model comparison, following DR group
- Valère Lambert joined leadership in 2021; Taeho/Pierre/Prithvi/Mohamed are now co-leading

# Benchmark Progress

Collaboration, workshop & benchmark

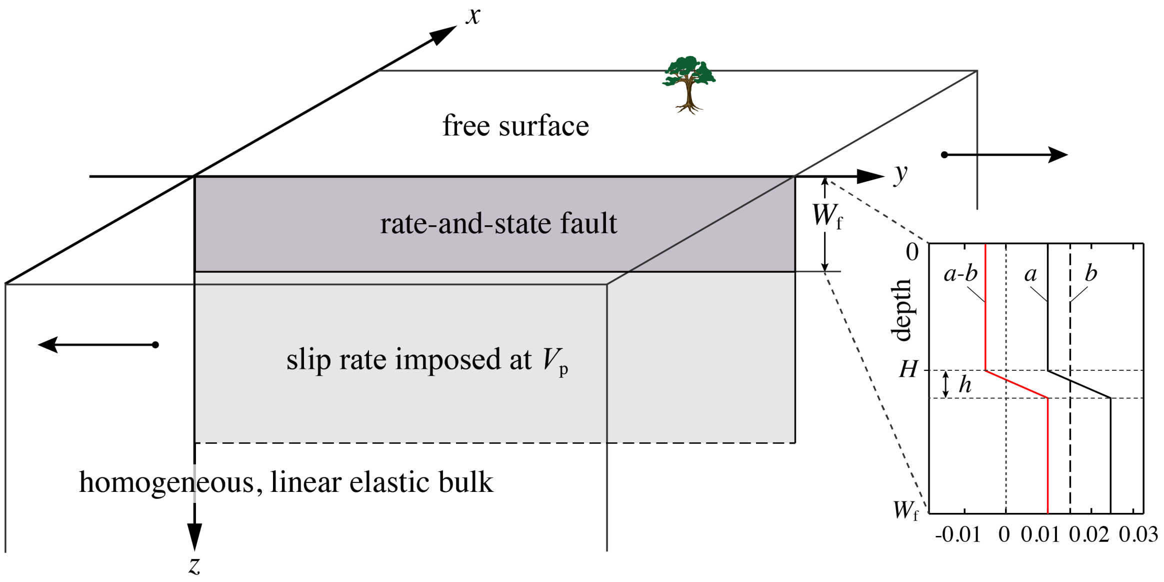
# Group progress over the years

- About 110 people are included on our email list
- **Six SCEC-funded workshops** since 2018
- **Eight benchmarks** (BP1–BP7) are now available online; more in development
- **Publications**
  - *Erickson, Jiang et al.*, 2020, SRL (24 coauthors) – group initiative & event size variability
  - *Jiang et al.*, 2022, JGR (19 coauthors) – 3D effects
  - *Erickson et al.*, 2023, BSSA (33 coauthors) – dynamic and dipping fault effects
  - *Lambert et al.*, 2025, JGR (24 coauthors) – fluid/friction effects on aseismic slip

# Design benchmarks for code verification

- **Guidelines**
  - Start simple & incrementally increase model complexity
  - Draw collaboration experience from SCEC community, especially DR 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-QD

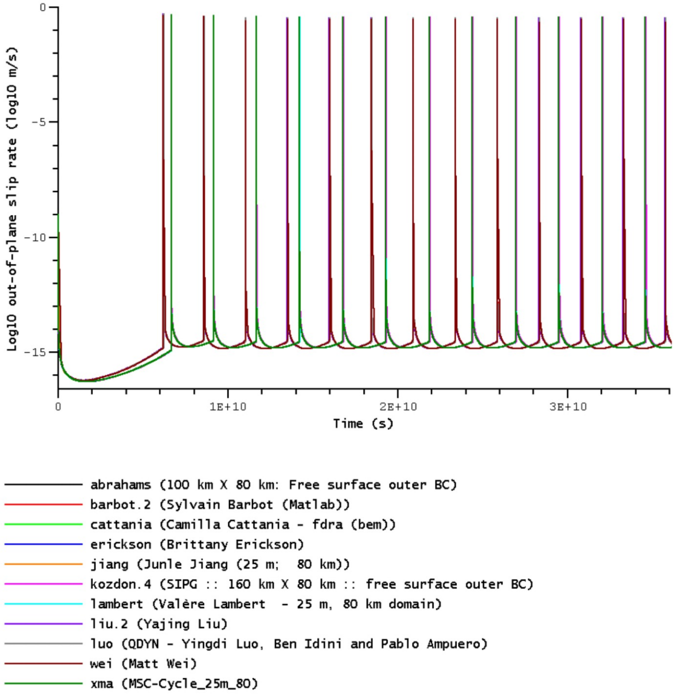



based on Rice, 1993

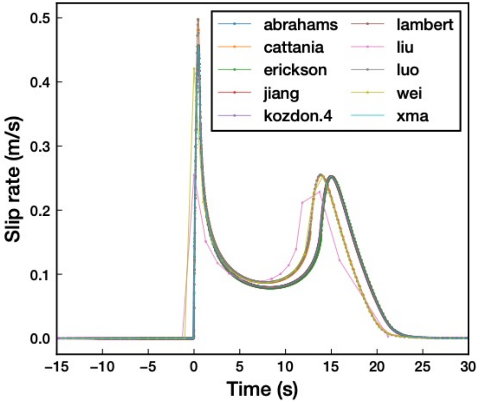
- **2D** anti-plane problem
- **1D** vertical strike-slip fault in a homogeneous half-space
- Rate-and-state friction with the aging evolution law
- **Quasi-dynamic** earthquakes
- Define a mathematical problem, leaving computational implementation up to modelers
- Request simulations at preferred resolutions (and more for tests)

# Benchmark exercises – how to compare models?

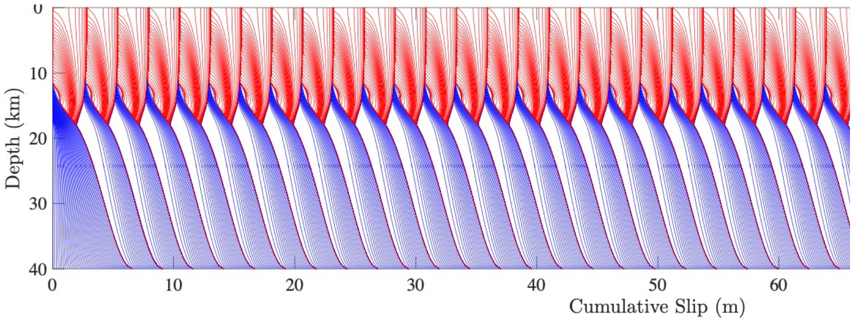
long-term evolution of slip/rate/stress




coseismic evolution of slip rate and stress




Slip evolution along depth



# Benchmark Progression

- BP2-QD: BP1-QD with a smaller nucleation size – Small & large events
- BP3-QD: 2D in-plane quasi-dynamic problem with a dipping fault – Role of fault geometry
- BP1-FD: Fully dynamic version of BP1-QD – Elastodynamics vs radiation damping
- BP4/BP5-QD: 3D quasi-dynamic problems for BP1-QD – 3D effects in whole-/half-space
- BP6-QD-A/S/C: 2D fluid-induced aseismic slip – Roles of friction laws and fluids
- BP7: 3D circular-asperity problem with different friction laws – Repeating earthquakes

In Development:

- BP8: 3D fluid injection – Induced seismicity
- BP9: 2D/3D dipping fault with depth-varying effective normal stress (SCEC/CRESCENT)

# What constitutes a successful benchmark?

**Persistent Numerical Challenges**

- Variable time-stepping
- Choices in computational domain size and boundary conditions
- Problem nonlinearity and round-off errors
- How to determine legitimate solution differences?
- Resolution of key spatial/temporal scales
- Numerical efficiency and computational speed

**Useful Findings**

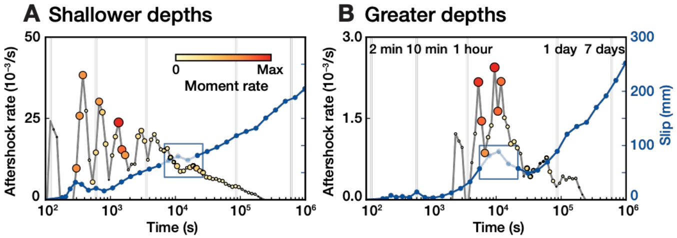
- Numerical resolutions change earthquake size distributions (Erickson, Jiang et al., 2020)
- Model-dependent loading rates affect event sequence timing, more than recurring event size (Jiang et al., 2023)
- Elastodynamics produce qualitative model differences (Erickson et al., 2023)
- A suite of quantitative error metrics (Erickson et al., 2023)
- Slip transients depend on time stepping and friction laws (Lambert et al., 2025)

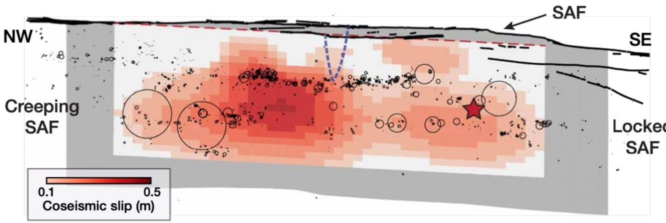
# Toward Validation

Some thoughts on relevance to lab friction benchmarks

# Validation from Field Observations

## Continuous Temporal Evolution



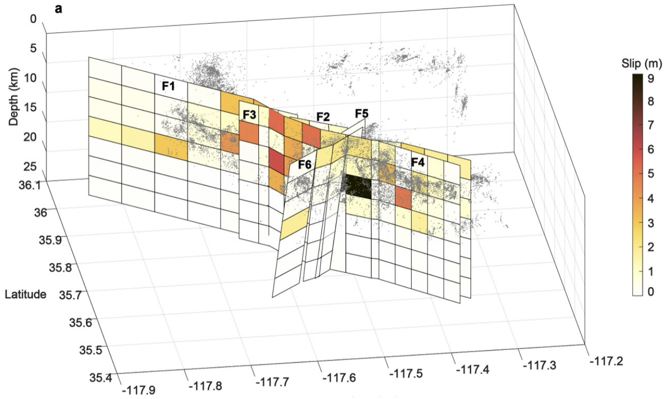

Parkfield

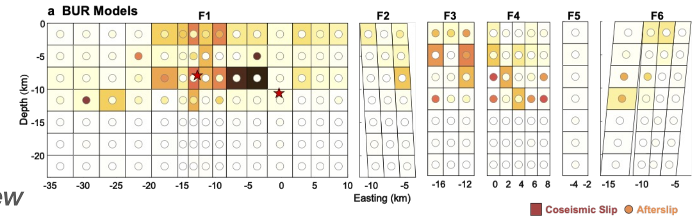
*Jiang et al., 2021*

How friction changes with loading rates and depth?

*Interplay of Seismic-Aseismic Fault Processes*

## Heterogeneous Spatial Pattern




Ridgecrest

*Zhao & Jiang, in review*

How friction changes at low/high rates and control source heterogeneity?

# SEAS Models ⇔ Field and Lab Observations

- **Use lab/field data to bear on the SEAS model design/input**
  - **Seismology/geodesy/geology**: Deformation, structure, seismicity, ground motion, …
  - **Rock mechanics:** friction laws, bulk rheology, …
  - The effective friction laws and frictional properties (and their spatial/temporal variations) are critical constraints in SEAS models

- **Target lab observations with SEAS model outputs?**
  - Reproduce lab data to understand model variability/discrepancy
  - Simulate lab scenarios to understand experimental/physical factors