

Community-Driven Code Comparisons for Three-Dimensional Dynamic Modeling of Sequences of Earthquakes and Aseismic Slip (SEAS)

Junle Jiang¹, Brittany A. Erickson², Valère R. Lambert³,
Jean-Paul Ampuero⁴, Ryosuke Ando⁵, Sylvain D. Barbot⁶, Camilla Cattania⁷,
Luca Dal Zilio^{8,9}, Benchun Duan¹⁰, Eric M. Dunham¹¹, Alice-Agnes Gabriel^{12,13},
Nadia Lapusta⁸, Duo Li¹², Meng Li¹⁴, Dunyu Liu¹⁵, Yajing Liu¹⁶,
So Ozawa⁵, Casper Pranger^{9,12}, Ylona van Dinther^{9,14}

¹School of Geosciences, University of Oklahoma, Norman, OK, USA

²Department of Computer and Information Science, University of Oregon, Eugene, OR, USA

³Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA, USA

⁴Université Côte d'Azur, IRD, CNRS, Observatoire de la Côte d'Azur, Géoazur, France

⁵Department of Earth and Planetary Science, University of Tokyo, Japan

⁶Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA

⁷Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

⁸Seismological Laboratory and Department of Mechanical and Civil Engineering,
California Institute of Technology, Pasadena, CA, USA

⁹Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

¹⁰Department of Geology and Geophysics, Texas A&M University, College Station, TX, USA

¹¹Department of Geophysics, Stanford University, Stanford, CA, USA

¹²Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München, Munich, Germany

¹³Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography,
University of California, San Diego, CA, USA

¹⁴Department of Earth Sciences, Utrecht University, Utrecht, Netherlands

¹⁵Institute for Geophysics, University of Texas at Austin, TX, USA

¹⁶Department of Earth and Planetary Sciences, McGill University, Montréal, QC, Canada

Key Points:

- We pursue community efforts to develop code verification benchmarks for three-dimensional earthquake rupture and crustal faulting problems
- We assess the agreement and discrepancies of seismic and aseismic fault behavior among simulations based on different numerical methods
- Our comparisons lend confidence to numerical codes and reveal sensitivities of model observables to key computational and physical factors

Abstract

Dynamic modeling of sequences of earthquakes and aseismic slip (SEAS) provides a self-consistent, physics-based framework to connect, interpret, and predict diverse geophysical observations across spatial and temporal scales. Amid growing applications of SEAS models, numerical code verification is essential to ensure reliable simulation results but is often infeasible due to the lack of analytical solutions. Here, we develop two benchmarks for three-dimensional (3D) SEAS problems to compare and verify numerical codes based on boundary-element, finite-element, and finite-difference methods, in a community initiative. Our benchmarks consider a planar vertical strike-slip fault obeying a rate- and state-dependent friction law, in a 3D homogeneous, linear elastic whole-space or half-space, where spontaneous earthquakes and slow slip arise due to tectonic-like loading. We use a suite of quasi-dynamic simulations from 10 modeling groups to assess the agreement during all phases of multiple seismic cycles. We found excellent quantitative agreement among simulated outputs for sufficiently large model domains and fine grid spacings. However, discrepancies in rupture fronts of the initial event are influenced by the free surface and various computational factors. The recurrence intervals and nucleation phase of later earthquakes are particularly sensitive to numerical resolution and domain-size-dependent loading. Despite such variability, key properties of individual earthquakes, including rupture style, duration, total slip, peak slip rate, and stress drop, are comparable among even marginally resolved simulations. Our benchmark efforts offer a community-based example to improve numerical simulations and reveal sensitivities of model observables, which are important for advancing SEAS models to better understand earthquake system dynamics.

Plain Language Summary

Fault zone and earthquake processes involve time scales ranging from milliseconds to millennia and longer. Increasingly, computational models are used to simulate sequences of earthquakes and aseismic slip (SEAS). These simulations can be connected to diverse geophysical observations, offering insights into earthquake system dynamics. To improve these simulations, we pursue community efforts to design benchmarks for 3D SEAS problems. We involve earthquake researchers around the globe to compare simulation results using different numerical codes. We identify major factors that contribute to the discrepancies among simulations. For example, the spatial dimension and resolution of the computational model can affect how earthquakes start and grow, as well as how frequently they recur. Code comparisons are more challenging when we consider the Earth's surface in the simulations. Fortunately, we found that several key characteristics of earthquakes are accurately reproduced in simulations, such as the duration, total movement, maximum speed, and stress change on the fault, even when model resolutions are not ideal. These exercises are important for promoting a new generation of advanced models of earthquake processes. Understanding the sensitivity of

69 simulation outputs will help test models against real-world observations. Our community efforts
70 can serve as a useful example to other geoscience communities.

71 **1 Introduction**

72 Physics-based computational models of dynamic processes in the Earth are increasingly used
73 to understand and predict observations from the lab and field across spatial and temporal scales,
74 addressing fundamental questions in various branches of solid Earth research. In earthquake science,
75 models of earthquake source processes are aimed at capturing dynamic earthquake ruptures from
76 seconds to minutes and slow slip processes subject to short-term anthropogenic or environmental
77 forcing, or tectonic loading over timescales of years and longer. For individual earthquakes, *dynamic*
78 *rupture simulations* have emerged as powerful tools to reveal the influence of fault structure, geometry,
79 constitutive laws, and prestress on earthquake rupture propagation and associated ground motion
80 (e.g., *Bhat et al., 2007; Day, 1982; Duan and Day, 2008; Dunham et al., 2011a,b; Gabriel et al.,*
81 *2012; Kozdon and Dunham, 2013; Lozos et al., 2011; Ma and Elbanna, 2019; Nielsen et al., 2000;*
82 *Olsen et al., 1997; Ripperger et al., 2007; Shi and Day, 2013; Wollherr et al., 2019; Xu et al., 2015*).
83 These simulations are limited to single-event scenarios and subject to imposed artificial prestress
84 conditions and ad hoc nucleation procedures. For larger-scale fault network systems, a group of
85 *earthquake simulators* aims at producing complex spatiotemporal characteristics of seismicity over
86 millennial time scales (*Richards-Dinger and Dieterich, 2012; Tullis et al., 2012*). The formidable
87 computational demand inevitably requires simplification and approximation of some key physical
88 features that could potentially influence or dominate earthquake and fault interactions, such as
89 seismic waves, slow slip, and inelastic responses.

90 To reveal earthquake system dynamics, it has been widely recognized that we need models
91 that simulate fault behavior over multiple seismic events and the intervening periods of aseismic
92 deformation. To address this need, numerical simulations of Sequences of Earthquakes and Aseismic
93 Slip (SEAS) are developed to consider all phases of earthquake faulting, from slow loading to
94 earthquake nucleation, propagation and termination over time scales of milliseconds to millenniums
95 in a unified, self-consistent framework (Figure 1). While retaining computational rigor, SEAS
96 models capture the pre-, inter-, and post-seismic slip and the resulting stress redistribution that
97 ultimately lead to spontaneous earthquake nucleation and dynamic ruptures. SEAS models can also
98 incorporate other physical processes relevant to long-term slip such as interseismic healing of the
99 fault zone, folding, viscoelasticity, and fluid flow (e.g., *Allison and Dunham, 2018; Barbot, 2018;*
100 *Lambert and Barbot, 2016; Sathiakumar et al., 2020; Zhu et al., 2020*). This modeling framework
101 can help determine and quantify which physical factors control diverse observables such as ground
102 deformation and shaking, and the frequency, size, and rupture style of microseismicity and large
103 earthquakes. SEAS modeling also bridges the domains of dynamic rupture simulations and earthquake

104 simulators, providing physically justified approximations and self-consistent choices on initial
 105 conditions and earthquake nucleation procedures.

106 Developments in SEAS models over the past two decades have led to increased diversity and
 107 complexity of models and closer connections between simulations and observations from the lab
 108 and field. For example, seismological and geodetic observations have been combined with models
 109 of seismic and aseismic deformation to study fault frictional properties (e.g., *Barbot et al.*, 2009;
 110 *Dublanchet et al.*, 2013; *Floyd et al.*, 2016; *Jiang and Fialko*, 2016; *Johnson et al.*, 2006; *Mitsui*
 111 *and Iio*, 2011), aftershock sequences (e.g., *Perfettini and Avouac*, 2004, 2007), tremor and slow slip
 112 (e.g., *Dublanchet*, 2018; *Luo et al.*, 2017; *Mele Veedu and Barbot*, 2016; *Tymofyeyeva et al.*, 2019;
 113 *Wang and Barbot*, 2020), and characteristics of small and large earthquake ruptures (e.g., *Barbot*
 114 *et al.*, 2012; *Cattania and Segall*, 2019; *Chen and Lapusta*, 2009; *Jiang and Lapusta*, 2016, 2017).
 115 The framework of earthquake sequence modeling is also adopted in diverse settings, which include
 116 subduction zones (e.g., *Hori et al.*, 2004; *Liu and Rice*, 2005, 2007; *Li and Liu*, 2016, 2017; *Noda*
 117 *et al.*, 2013; *Shi et al.*, 2020; *Van Dinther et al.*, 2013), collision zones (e.g., *Dal Zilio et al.*, 2018;
 118 *Michel et al.*, 2017; *Qiu et al.*, 2016), and induced seismicity phenomena (e.g., *Dieterich et al.*,
 119 2015; *McClure and Horne*, 2011), among many applications.

120 While researchers continue to build more advanced and detailed SEAS models, verification
 121 of different numerical codes is essential to ensure credible and reproducible results, and sustain
 122 scientific progress. In practice, analytical solutions are generally not available, even for simple
 123 SEAS problems, and convergence of simulations to a high-resolution reference case may not always
 124 detect systematic issues in complex numerical codes. An alternative means for verifying model
 125 results are comparisons of independent numerical codes from different research groups. As an
 126 example, the SCEC/USGS Spontaneous Rupture Code Verification Project pioneered the code
 127 comparison exercise and improved confidence in the outcomes of dynamic rupture simulations
 128 (*Barall and Harris*, 2014; *Harris et al.*, 2009, 2018).

129 Verification of SEAS models is confronted with distinct challenges, due to the wide range of
 130 temporal and spatial scales that characterize the earthquake source behavior and the diversity of
 131 numerical algorithms and codes. For example, codes based on spectral boundary element method
 132 (SBEM) (*Barbot*, 2021; *Lapusta and Rice*, 2003; *Lapusta and Liu*, 2009) are highly efficient in
 133 solving for dynamic earthquake ruptures, albeit with relatively simple fault geometry and bulk.
 134 Codes based on boundary element method (BEM) (e.g., *Goswami and Barbot*, 2018; *Kato*, 2016;
 135 *Liu*, 2013; *Luo et al.*, 2017; *Nakata et al.*, 2012; *Rice and Tse*, 1986; *Segall and Bradley*, 2012; *Tse*
 136 *and Rice*, 1986) can efficiently simulate earthquake ruptures in problems with more complex fault
 137 geometry, often with the approximation of inertia (i.e., “quasi-dynamic” earthquakes). Codes based
 138 on the finite difference method (FDM) (e.g., *Allison and Dunham*, 2018; *Erickson and Dunham*,
 139 2014; *Erickson et al.*, 2017; *Mckay et al.*, 2019; *Pranger*, 2020), finite element method (FEM)

(e.g., [Liu et al., 2020](#); [Luo et al., 2020](#); [Tal and Hager, 2018](#)), spectral element method (SEM) (e.g., [Kaneko et al., 2011](#); [Thakur et al., 2020](#)), and hybrid methods (e.g., [Abdelmeguid et al., 2019](#)) can flexibly incorporate geometrical and structural complexity in earthquake simulations, usually at a greater computational cost than BEM. For all these codes, common challenges lie in the interaction between the highly nonlinear nature of the SEAS problems and numerical round-off errors, which can lead to the divergence of model behaviors with increasing simulation time. Simulation techniques are further complicated when additional physical factors, e.g., structural complexity, material heterogeneities, and bulk inelastic responses, are incorporated or approximated. However, considering such complexity may be crucial in our efforts to understand earthquakes and predict seismic hazards.

We reported our efforts in the SEAS initiative—a working group funded by the Southern California Earthquake Center (SCEC) to perform community code verification exercises for SEAS models—and results from our first two benchmarks, BP1 and BP2, for two-dimensional (2D) SEAS problems in [Erickson et al. \(2020\)](#). We gathered 11 independent modeling groups using different numerical codes to participate and compare 2D SEAS simulations. Through code comparisons, we identified how various computational factors, e.g., the model domain size and boundary conditions, influence simulation results in 2D antiplane problems. Our exercises demonstrate an excellent agreement in simulations with a sufficiently large domain size and small grid spacing, lending confidence to the participating numerical codes. We also found that artificial complexity in earthquake patterns can arise due to insufficient numerical resolution for key physical length scales, although ensemble-averaged measures, such as earthquake recurrence times, are more robust than observables from individual simulations, even at poor numerical resolutions.

As our community and code capabilities grow, we have made substantial progress to create new benchmarks for three-dimensional (3D) SEAS problems. Here, we present our recent community-driven development of two new 3D benchmarks, BP4 and BP5, and code comparison results for the quasi-dynamic versions of these benchmarks. The dramatically increased computational demand for 3D problems requires us to balance the simplicity and realism of the benchmark problems (Section 2). We examine choices of numerical implementations among the modeling groups to ensure consistent comparisons of a large set of 3D simulations (Section 3). We also design new strategies and metrics for code verification for complex 3D simulations that are often done at the upper limit of numerical resolutions (Section 4). In particular, we explore the sensitivity of diverse model outputs and observables to major computational and physical factors. Through these efforts, we aim to improve and promote a new generation of rigorous, robust numerical codes for SEAS problems, and to potentially inform and interact with other communities that are tackling similar challenges in nonlinear multiscale, multi-physics problems (e.g. [Buitier et al., 2016](#); [Matsui et al., 2016](#); [Maxwell et al., 2014](#); [Nearing et al., 2018](#)).

175 **2 Community Benchmark Development**

176 **2.1 Strategy for Benchmark Design**

177 We follow the principle to start simple and add incremental complexity in the design process
178 of SEAS benchmarks. For 2D benchmark problems (BP1 and BP2), we considered a 1D fault in
179 a 2D antiplane setting to explore how the computational domain size and boundary conditions
180 affect simulation results and how numerical resolution influences earthquake patterns and statistics
181 (*Erickson et al., 2020*). Overall, we aim to verify different numerical codes through a detailed
182 comparison of simulated fault behavior over multiple time scales. These efforts require a better
183 understanding of the dependence of fault slip history on fault properties, friction laws, initial conditions,
184 model spin-up, and other factors.

185 Our findings and experience from 2D benchmark exercises prepared us for more complicated
186 3D benchmark problems. We need to design 3D benchmarks that are tractable for the widest suite
187 of numerical codes and thereby maximize participation of modelers, especially considering the
188 higher computational cost of 3D simulations and distinct capabilities of different codes in the community.
189 For example, codes based on the spectral boundary element method, e.g., BICycle (*Lapusta and*
190 *Liu, 2009*), are efficient in solving for quasi-dynamic or fully dynamic earthquake ruptures, but
191 rely on periodic boundary conditions and free surface approximations. Methods based on the finite
192 element method, e.g., EQsimu (*Liu et al., 2020*), can incorporate more complicated fault geometries
193 and bulk, including a rigorous treatment of the free surface, but may need to balance the domain
194 size with a reasonable computational cost.

195 Since the participation of many modelers is essential to the success of the code verification
196 exercise, we sought to build a consensus in the community at the very beginning of our benchmark
197 design process. We conducted surveys among the interested modelers to decide on the most preferred
198 benchmark problems. For instance, we have chosen to focus on quasi-dynamic problems for our
199 initial 3D benchmarks, BP4 and BP5, seeing that many numerical codes cannot yet incorporate
200 full inertial effects but adopt the radiation damping approximation (*Rice, 1993*). While we assess a
201 myriad of simulation outputs and develop metrics for model comparisons, we are flexible about the
202 submitted simulation data, given that sometimes substantial code development is needed. During
203 the subsequent development following initial comparisons of benchmark BP4, we learned lessons
204 about the computational cost and have accordingly revised the model parameters and output types
205 for benchmark BP5, hence some minor differences exist between the two benchmarks.

206 **2.2 Benchmark Problem Setup**

207 We developed two benchmarks, BP4 and BP5, for 3D SEAS simulations (Figure 2). Our first
208 3D benchmark problem, BP4, considers a 3D homogeneous, isotropic, linear elastic whole space

209 in \mathbb{R}^3 , defined by $\mathbf{x} = (x_1, x_2, x_3) \in (-\infty, \infty)^3$, where x_1 , x_2 , and x_3 refer to the coordinates in the
 210 fault-normal, along-strike, and along-depth directions, respectively. A vertical strike-slip fault
 211 is embedded at $x_1 = 0$. We use the notation “+” and “-” to refer to the side of the fault with x_1
 212 positive and negative, respectively. We assume 3D motion, denoting components of the displacement
 213 vector \mathbf{u} as $u_i = u_i(\mathbf{x}, t)$, $i = 1, 2, 3$, in the i -direction. The second 3D benchmark problem, BP5,
 214 involves a fault with half the vertical dimension in a 3D half-space, defined by $\mathbf{x} = (x_1, x_2, x_3) \in (-\infty, \infty) \times (-\infty, \infty) \times (0, \infty)$,
 215 with a free surface at $x_3 = 0$ and x_3 as positive downward. Several model parameters in BP5 are
 216 adjusted to allow for reduced computational demand compared with BP4.

217 Each benchmark problem branches into two versions, depending on the treatment of the inertial
 218 effect, i.e., quasi-dynamic (QD) or fully dynamic (FD) earthquake ruptures, which are assigned
 219 with different suffixes in benchmark names (e.g., BP4-QD or BP4-FD). Full descriptions of these
 220 benchmarks are available online on the SEAS code comparison platform ([https://strike.
 221 scec.org/cvws/seas/](https://strike.scec.org/cvws/seas/)) and also included here as supplementary materials. We summarize below
 222 the governing equations, constitutive laws, and initial and fault interface conditions that are important
 223 for understanding SEAS simulations for both QD and FD problems, and related numerical resolution
 224 issues. For better consistency and clarity, we changed a few notations from the original benchmark
 225 descriptions.

226 The 3D fault zone motion is governed by the momentum balance equation, or the equilibrium
 227 equation if inertia is neglected:

$$228 \quad \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \boldsymbol{\sigma} \quad \text{for FD problems;} \quad (1a)$$

$$229 \quad 0 = \nabla \cdot \boldsymbol{\sigma} \quad \text{for QD problems,} \quad (1b)$$

231 where \mathbf{u} is the displacement vector, $\boldsymbol{\sigma}$ is the stress tensor, and ρ is the material density. Hooke’s
 232 law relates stresses to strains by

$$233 \quad \sigma_{ij} = K \epsilon_{kk} \delta_{ij} + 2\mu \left(\epsilon_{ij} - \frac{1}{3} \epsilon_{kk} \delta_{ij} \right), \quad i, j = 1, 2, 3, \quad (2)$$

234 where K and μ are the bulk and shear moduli, respectively. The strain-displacement relations are
 235 given by

$$236 \quad \epsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad i, j = 1, 2, 3. \quad (3)$$

237 **2.2.1 Boundary and Interface Conditions**

238 We have a boundary condition at the surface ($x_3 = 0$) (for only BP5) and an interface condition
 239 on the fault ($x_1 = 0$). At the free surface, all components of the traction vector are zeros, namely

$$240 \quad \sigma_{j3}(x_1, x_2, 0, t) = 0, \quad j = 1, 2, 3. \quad (4)$$

241 We assume no-opening on the fault, namely

$$242 \quad u_1(0^+, x_2, x_3, t) = u_1(0^-, x_2, x_3, t), \quad (5)$$

and define the slip vector as the jump in horizontal and vertical displacements across the fault:

$$s_j(x_2, x_3, t) = u_j(0^+, x_2, x_3, t) - u_j(0^-, x_2, x_3, t), \quad j = 2, 3, \quad (6)$$

with right-lateral motion yielding positive values of s_2 . Positive values of s_3 and s_2 occur when the “+” or “-” side of fault moves in the positive or negative x_3 and x_2 directions, respectively.

We require that components of the traction vector be equal and opposite across the fault, which yields the following conditions:

$$\sigma_{j1}(0^+, x_2, x_3, t) = \sigma_{j1}(0^-, x_2, x_3, t), \quad j = 1, 2, 3, \quad (7)$$

and denote the common values $-\sigma_{11}$, σ_{21} , and σ_{31} by σ (positive in compression), τ_y , and τ_z , respectively, i.e. one normal traction component and two shear traction components. Note that positive values of τ_y indicate stress that drives right-lateral faulting and positive values of τ_z indicates stress that tends to cause the “+” side of the fault to move downward in the positive x_3 direction and the “-” side to move upward.

We define the slip rate vector \mathbf{V} in terms of its components, $\mathbf{V} = (V_2, V_3) = (\dot{s}_2, \dot{s}_3)$, where the dot notation indicates the time derivative, and denote slip rate amplitude as the norm of the slip rate vector, $V = \|\mathbf{V}\|$. The shear stress vector is given by $\boldsymbol{\tau} = (\tau_y, \tau_z)$.

In both benchmark problems, we assign a frictional domain on the fault Ω_f with a finite size of (l_f, W_f) , where fault slip is governed by a rate- and state-dependent friction law ([Dieterich, 1979](#); [Ruina, 1983](#); [Marone, 1998](#)). The shear stress on the frictional fault $\boldsymbol{\tau}$ is set to always equal the frictional strength $\mathbf{F} = (F_2, F_3)$, namely

$$\boldsymbol{\tau} = \mathbf{F}(\bar{\sigma}_n, \mathbf{V}, \theta), \quad (8)$$

where $\bar{\sigma}_n$ is the effective normal stress and θ is a state variable.

For quasi-dynamic problems (BP4-QD and BP5-QD), $\boldsymbol{\tau} = \boldsymbol{\tau}^0 + \Delta\boldsymbol{\tau} - \eta\mathbf{V}$ is the sum of the prestress $\boldsymbol{\tau}^0$, the shear stress change due to quasi-static deformation $\Delta\boldsymbol{\tau}$, and the radiation damping approximation of inertia $\eta\mathbf{V}$ ([Rice, 1993](#)), where $\eta = \mu/2c_s$ is half the shear-wave impedance for shear wave speed $c_s = \sqrt{\mu/\rho}$, with the shear modulus μ and density ρ . For fully dynamic problems, $\boldsymbol{\tau} = \boldsymbol{\tau}^0 + \Delta\boldsymbol{\tau}$, where $\Delta\boldsymbol{\tau}$ includes all elastodynamic stress transfers due to prior slip on the fault.

The frictional resistance of the fault is the product of the effective normal stress and evolving friction coefficient f on the fault, $\bar{\sigma}_n$, namely

$$\mathbf{F}(\bar{\sigma}_n, \mathbf{V}, \theta) = \bar{\sigma}_n f(V, \theta) \mathbf{V}/V. \quad (9)$$

The effective normal stress is taken to be uniform in space and assumed to be time-independent, which is valid due to the symmetry across the fault and the assumption of no fault opening. We

adopt a regularized formulation for the rate-and-state friction coefficient (*Lapusta et al., 2000*)

$$f(V, \theta) = a \sinh^{-1} \left[\frac{V}{2V_0} \exp \left(\frac{f_0 + b \ln(V_0\theta/L)}{a} \right) \right], \quad (10)$$

where L is the characteristic state evolution distance, f_0 is the reference friction coefficient determined at the reference slip rate V_0 , and a and b are the parameters for the direct and evolutionary effects, respectively. We couple Eq. 10 with the aging law for the evolution of the state variable (*Dieterich, 1979; Ruina, 1983*):

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}, \quad (11)$$

The spatial distributions of parameters a and b are chosen to create a seismogenic zone with velocity-weakening (VW, $a - b < 0$) frictional properties that is surrounded by areas with velocity-strengthening (VS, $a - b > 0$) frictional properties, with a linear transition zone in-between.

Outside the frictional domain Ω_f , we impose a fixed long-term fault slip rate, which we refer to as the plate loading rate V_L , giving rise to the interface conditions:

$$V_2(x_2, x_3, t) = V_L, \quad (12a)$$

$$V_3(x_2, x_3, t) = 0, \quad (12b)$$

At an infinite distance from the fault ($|x_1| \rightarrow \infty$), the far-field displacements should follow:

$$u_2^\pm = \pm \frac{V_L t}{2}, \quad (13a)$$

$$u_1 = u_3 = 0, \quad (13b)$$

where the superscript “ \pm ” refers to the “+/-” sides of the fault, associated with positive and negative displacement values, respectively. By imposing this boundary condition, we consider displacements \mathbf{u} that are only caused by slip, excluding the deformation that produced the prestress τ^0 in the absence of fault slip. As a result, σ are essentially stress changes associated with the displacement field \mathbf{u} relative to the prestress state. We describe an infinitely large model domain in our benchmark problems and leave choices of numerical implementation and approximation to modelers (see section 3.1).

2.2.2 Initial Conditions

We choose the initial values of the stress and state on the fault to enable a spatially uniform distribution of initial fault slip rates, given by

$$\mathbf{V} = (V_{\text{init}}, V_{\text{tiny}}), \quad (14)$$

where we assign $V_{\text{init}} = V_L$ for simplicity and $V_{\text{tiny}} = 10^{-20}$ m/s to avoid infinity in logarithmic slip rates. To achieve this, we prescribe the initial state over the entire fault with the steady-state value at the slip rate V_{init} , namely

$$\theta(x_2, x_3, 0) = L/V_{\text{init}}. \quad (15)$$

307 Accordingly, the initial stress vector takes the form $\boldsymbol{\tau}^0 = \tau^0 \mathbf{V}/V$, where the scalar pre-stress τ^0 is
 308 the steady-state stress:

$$309 \tau^0 = \bar{\sigma}_n a \sinh^{-1} \left[\frac{V_{\text{init}}}{2V_0} \exp \left(\frac{f_0 + b \ln(V_0/V_{\text{init}})}{a} \right) \right] + \eta V_{\text{init}}. \quad (16)$$

311 For quasi-dynamic problems, we need to specify an initial value for slip, which we take to be
 312 zero, namely

$$313 s_j(x_2, x_3, 0) = 0, \quad j = 2, 3. \quad (17)$$

314 For fully dynamic problems, initial values for displacements and velocities in the medium need
 315 to be specified. We spare the details here since our code comparisons below will be limited to
 316 quasi-dynamic problems BP4-QD and BP5-QD.

317 To break the lateral symmetry of the fault and facilitate code comparisons, we add a square
 318 zone within the VW region, with a width of $w = 12$ km and centers at $(-22.5$ km, -7.5 km) in BP4
 319 and $(-24$ km, -10 km) in BP5, as a forced nucleation location for the first simulated earthquake. To
 320 do that, we impose a higher initial slip rate, V_i , in the x_2 direction within this square zone while
 321 keeping the initial state variable $\theta(x_2, x_3, 0)$ unchanged. The resultant higher pre-stress can be
 322 calculated by replacing V_{init} with V_i in Eq. 16. This initial condition leads to an immediate initiation
 323 of the first event. In BP5, we additionally use a smaller characteristic state evolution distance L
 324 in this forced nucleation zone to promote the nucleation of subsequent earthquakes in the same
 325 areas (see the next section). We note that it will be interesting for future benchmarks to use a ramp
 326 function instead of a step function for the nucleation zone to unify spatial discretization of the
 327 nucleation zone ([Galis et al., 2015](#)).

328 In simulations, the governing equations (1)–(3) are solved along with interface conditions (4)
 329 (for only BP5) and (5)–(13), and initial conditions (14)–(17) over the period $0 \leq t \leq t_f$, where t_f is
 330 the maximum simulation time. Numerical methods that truncate model domain in the fault-normal
 331 direction also need to explicitly incorporate the far-field boundary conditions on asymptotic behavior
 332 of displacements at infinity (see section 3.1). All model parameters in benchmarks BP4-QD and
 333 BP5-QD are listed and compared in Table 1.

334 2.2.3 Critical Physical Length Scales

335 Numerical resolution is a critical issue for 3D benchmark problems, as we need to balance the
 336 computational cost and adequate resolution to achieve acceptable model agreement. Two physical
 337 length scales are generally important to consider in these problems. The first length scale, often
 338 referred to as the process zone or cohesive zone, Λ , describes the spatial region near the rupture
 339 front under which breakdown of fault resistance occurs, and shrinks as ruptures propagate faster
 340 ([Freund, 1998](#); [Palmer and Rice, 1973](#); [Day et al., 2005](#)). For faults governed by the rate-and-state

friction, the quasi-static process zone at a rupture speed of 0^+ , Λ_0 , can be estimated as follows (Ampuero and Rubin, 2008; Perfettini and Ampuero, 2008):

$$\Lambda_0 = C \frac{\mu L}{b \sigma_n}, \quad (18)$$

where C is a constant of order 1.

The second length scale that controls model behavior is the critical nucleation zone size h^* , which determines the minimum dimension of the velocity-weakening region over which spontaneous nucleation may occur (Ampuero and Rubin, 2008; Andrews, 1976a,b; Day, 1982; Rubin and Ampuero, 2005). For 3D problems, the critical nucleation size can be estimated for the aging law for $0.5 < a/b < 1$ as follows (Chen and Lapusta, 2009):

$$h^* = \frac{\pi}{2} \frac{\mu b L}{(b - a)^2 \sigma_n}. \quad (19)$$

Using Eqs. 18 and 19, we estimate that the nucleation zone size is 12.4 km and 12.5 km within the VW region (outside the zone of frictional heterogeneity) in BP4 and BP5, respectively, whereas the process zone is 2 and 6 km, respectively. This allows us to suggest a grid spacing of 500 m and 1000 m for low-order accurate methods for BP4 and BP5, respectively, which resolve Λ_0 with at least four grid points in both benchmarks, following suggestions by Day et al. (2005).

The two benchmark problems are designed to produce a periodic sequence of spontaneous earthquakes and slow slip, following the first event in which we impose higher local slip rates to kickstart the earthquake rupture. BP5 is slightly different from BP4 in that the state evolution distance is reduced within a square zone within the VW region, resulting in a smaller nucleation size, $h^* = 11.6$ km. This form of persistent frictional heterogeneity is introduced to favor (but not always determine) the initiation of subsequent earthquakes at the same location. We choose the total simulation time to produce up to eight large earthquakes in the simulations, which allows us to examine not only a few early events but also the seismic behavior of the fault in the longer term.

2.3 Model Outputs

To assess model behavior over disparate spatial and temporal scales, we design several types of simulation outputs for these benchmarks (Figure 3): (1) time series of local on-fault and off-fault properties, (2) time series of global source properties, (3) a catalog of earthquake characteristics, (4) profiles of slip accumulation and stress evolution, and (5) rupture times during the first event in the sequence. The output formats for coseismic observables follow the practice in the code verification of single-event dynamic rupture simulations (Harris et al., 2009).

For local time series data, we are mostly interested in resolving the time evolution of fault slip rates, shear stress, and off-fault displacements throughout the coseismic, postseismic, and interseismic periods. The “global” source properties refer to the evolving maximum slip rates and

374 moment rates over the entire seismogenic fault areas, which are useful for determining the precise
 375 time of initiation and cessation of individual earthquakes. The catalog data contain key characteristics
 376 of simulated earthquakes, including their initiation and termination times, coseismic slip, and stress
 377 drop. The beginning and end of the coseismic period are determined as the moments any point
 378 on the fault reaches above or all points drop below a threshold slip rate, V_{th} (chosen as 0.03 m/s),
 379 respectively. We then estimate coseismic slip and stress drop as the change in the amplitude of fault
 380 slip and shear stress (negative stress change for positive stress drop).

381 The slip and stress profiles in the along-strike and along-dip directions illustrate the general
 382 patterns of earthquake sequences and the partitioning of seismic and aseismic slip. The rupture
 383 time data record the time when each point on the fault reaches a certain threshold slip rate ($V_{th} =$
 384 0.03 m/s) during the first earthquake. Note that the relative rupture times are independent of V_{th}
 385 and we can use maximum slip rates and rupture time data to construct contours of rupture fronts
 386 associated with different values of V_{th} .

387 2.4 Modeling Groups

388 To maximize participation, we focus on the quasi-dynamic version of the 3D benchmarks and
 389 anticipate new comparisons in future as the computational capabilities of the community grow. A
 390 total of 10 modeling groups participated in the code comparisons for the quasi-dynamic problems,
 391 BP4-QD and BP5-QD, using nine different numerical codes. We summarize numerical codes and
 392 methods, modeling groups, and their participation in either or both benchmarks in Table 2. Note
 393 that the simulations hosted on our online platform are named after the username of the modeler
 394 who uploaded the data; we include the names here for reference.

395 We discussed preliminary code comparison results for 3D benchmarks in two workshops
 396 in January and October of 2020. We also used the opportunities to share scientific progress and
 397 decide on the directions of our future efforts, with substantial inputs from students and early career
 398 scientists. Our online platform (<https://strike.scec.org/cvws/seas/>) facilitates the initial
 399 comparison of benchmark results, where modelers can upload and immediately visualize time
 400 series data and rupture front contours to assess model agreements.

401 More modeling groups participated in BP5-QD than BP4-QD, due to considerations of timing
 402 and/or computational costs (Table 2). Given the similar problem setup of the two benchmarks, we
 403 present main results for BP4-QD and more complete comparisons for BP5-QD, using a selected
 404 suite of simulations listed in Tables 3 and 4. Due to limitations in code development and computational
 405 resources or different numerical methods, not all modeling groups have submitted all forms of
 406 requested simulation outputs. Our comparisons use the entire set of available simulation results.

3 Computational Factors

Both 3D SEAS benchmarks are computationally challenging: BP4-QD requires better numerical resolution and BP5-QD incorporates additional effects associated with the free surface. The overall high computational cost means that we have to carefully consider the effects of computational domain truncation and grid discretization on simulations that are performed near the marginal numerical resolutions. We elaborate on these computational factors in this section to provide important context to our code comparison results. We also comment on the time stepping schemes, an important ingredient in SEAS simulations.

3.1 Domain Truncation and Boundary Conditions

In the benchmark descriptions, we prescribe a whole space or semi-infinite half-space. All numerical codes need to truncate the computational domain in certain dimensions and adopt boundary conditions. While comprehensive tests about the effect of computational domain truncation and boundary conditions were conducted for our 2D benchmark problems (*Erickson et al., 2020*), they are less feasible for 3D SEAS simulations due to the much higher computational demand. We therefore let modelers determine sufficiently or reasonably large domain sizes using the suggested (or sometimes larger) grid spacing, with the aim of obtaining well-matching results. We denote the total model dimension in the fault-normal, along-strike, and along-dip directions as L_1 , L_2 , and L_3 , respectively, and list the domain size of all simulations in Tables 3 and 4.

In general, BEM/SBEM simulations only discretize the fault interface and solve for on-fault physical properties, implicitly incorporating bulk response via semi-analytical solutions. This feature avoids the need of domain truncation in the fault-normal direction; hence in Tables 3 and 4 we denote ∞ as the fault-normal dimension in BEM/SBEM simulations. Along lateral directions, BEM simulations with FDRA include three large elements outside the friction-controlled domain to construct semi-infinite loading zones of a dimension of 10^4 km. BEM simulations with ESAM, HBI, TriBIE, and Unicyle adopt same- or similar-sized elements and incorporate deep creep in the semi-infinite domain via a commonly used "backslip" approach, in which stress transfers are calculated for spatially-varying fault slip rates subtracted with V_L . Hence the down-dip dimensions in these simulations are effectively infinite, even though we list the actual dimension of the adopted computational domain in Tables 3 and 4.

BEM/SBEM simulations with ESAM, BICycle, and Motorcycle adopt periodic boundaries that effectively involve infinite replicas of the model domain in the along-strike direction; large areas with the imposed loading rate were included to minimize the effect of adjacent fault replicas on simulated fault behavior. Simulations with BICycle also have periodic boundary conditions in the along-depth direction and, in the half-space problem BP5, approximate the free surface by

441 adding a mirror image of the physical domain. Nonetheless, in our comparisons we do not observe
 442 systematic differences between BICyclE and other simulations that suggest the influence of this
 443 approximation.

444 For volume-discretized methods such as EQsimu and GARNET, modelers need to truncate
 445 model domains in all three dimensions. For the far-field boundaries in the fault-normal direction,
 446 EQsimu and GARNET simulations use a Dirichlet boundary conditions for displacements via a
 447 fixed slip rate. When truncated fault-normal dimensions are not sufficiently large, the results will
 448 be quantitatively influenced by this boundary condition. In BP5-QD, EQsimu modelers chose the
 449 steady interseismic velocity predicted by $V(x_1) = V_L/\pi \cdot \arctan(x_1/H)$ (*Savage and Burford, 1973*),
 450 specifically, $V \approx 4 \times 10^{-10}$ m/s (with $H = 18$ km and $x_1 = L_1/2 = 50$ km), to impose displacement
 451 boundary conditions in the far field. Both EQsimu and GARNET impose stress-free conditions at
 452 the remaining boundaries of the truncated domain, which includes two planes perpendicular to the
 453 fault and the bottom layer.

454 With computational resources as the only limiting factor, these different approaches are in
 455 principle compatible with the boundary conditions at infinity as outlined in our benchmark descriptions.
 456 In our code comparison exercises, we will consider the effects of domain truncation and boundary
 457 conditions, especially for marginally resolved simulations.

458 **3.2 Grid Discretization**

459 The two benchmarks, especially BP5-QD, have a relatively large grid spacing by design, which
 460 is a nontrivial factor when we compare different simulations. For example, different codes represent
 461 local fault properties within piece-wise constant (BEM) or piece-wise linear (FEM) elements, or
 462 on Fourier sample points (SBEM). In the former case, most BEM codes use rectangular elements,
 463 whereas TriBIE uses triangular elements with their centroids on irregular grids. Additionally, FDM
 464 code GARNET uses a staggered grid, which means that slip rates are not located on the same grid
 465 points with some other properties. Consequently, the representing grid points in these simulations
 466 are often offset from the observational points specified in the benchmark description. Even though
 467 these numerical codes are designed to solve the same continuum problem, different discrete representations
 468 of local physical properties, when combined with a large grid spacing, result in nontrivial truncation
 469 errors that are different among these codes.

470 During early code comparisons for BP5-QD, we noticed that a spatial offset in the computational
 471 grid can lead to noticeable differences in the location and size of the forced nucleation region and
 472 rupture front development during the first event. Even though we have improved the consistency in
 473 model setups through several iterations among modelers, the inherent differences in computational
 474 methods will contribute to model discrepancies. While this issue does not substantially affect our

475 2D benchmark problems (*Erickson et al., 2020*), it appears important in the comparisons for our 3D
 476 benchmarks, likely due to the use of larger cells.

477 **3.3 Time Stepping Schemes**

478 The schemes for non-uniform, adaptive time stepping are essential in SEAS simulations that
 479 resolve various stages of the seismic cycle. We do not cover this computational aspect in the benchmark
 480 description, and presume that modelers will adopt the optimal time stepping schemes for their
 481 numerical codes. Most codes use adaptive Runge-Kutta methods for time stepping. FDM code
 482 GARNET uses a linear multistep method (BDF2, second order backward differentiation formula)
 483 for their time stepping (*Pranger, 2020*). SBEM code BICyclE determines the adaptive time steps
 484 based on maximum slip rates and stability conditions derived from constitutive laws (*Lapusta et al.,*
 485 *2000*), which has also been adopted in other codes, such as EQsimu and GARNET.

486 In practice, suboptimal time stepping can complicate model comparisons. In earlier comparisons
 487 for BP4-QD, one BICyclE simulation (*jiang*) exhibited frequent aseismic transients prior to large
 488 events, while these features were absent in another BICyclE simulation (*Lambert*). We later tracked
 489 down the cause of this discrepancy: the latter simulation adopts a smaller constant factor in estimating
 490 the time step size (Eq. 18 in *Lapusta et al. (2000)*) and the use of finer time steps apparently eliminates
 491 the aseismic transients, which are numerical artifacts. We encountered a similar situation with
 492 EQsimu simulations, where a simple refinement of all time steps could remove numerical transients
 493 and improved model agreement. Since we have fixed this issue in updated models, the choice on
 494 time stepping approaches should have a minimal influence on the comparison results presented
 495 below.

496 **4 Comparisons of 3D Simulations**

497 We examine a range of simulation outputs in the two benchmarks to understand model sensitivities
 498 and verify different numerical codes. We first show the agreement and self-convergence of models
 499 in BP4-QD (Figures 4–6), followed by more complete comparisons for BP5-QD (Figures 4 and
 500 7–17). These comparisons include the rupture fronts of the first earthquake in the sequence (Figures 4
 501 and 7), the long-term fault behavior in terms of maximum slip rates and earthquake characteristics
 502 (Figures 5 and 9), cumulative slip profiles (Figures 6 and 8), on-fault local stress and slip rate evolution
 503 in the long term (Figures 10 and 11) and during the coseismic period (Figure 12 and 14), as well
 504 as off-fault displacement behavior (Figure 15). Furthermore, we explore the relationship between
 505 interseismic stressing history and earthquake recurrence intervals (Figure 16) and the resolvability
 506 of coseismic observables in simulations with different spatial resolutions (Figure 17).

507 **4.1 Whole-Space Problem BP4-QD**

508 **4.1.1 Initial Rupture Propagation**

509 The initial stage of the simulations provides a few crucial observables that are minimally affected
 510 by cumulating numerical errors. For benchmark BP4-QD, we first compare the coseismic rupture
 511 fronts during the first event in simulations with the suggested grid spacing ($\Delta x = 500$ m) (Figure 4a).
 512 We adopt a higher threshold slip rate than specified in the benchmarks, $V_{th} = 0.1$ m/s, to define the
 513 initiation time of the earthquake as the moment when any point on the fault reaches V_{th} ; we will
 514 later explore how a different V_{th} affects BP5-QD comparisons in section 4.2.1. In Figure 4a, we
 515 find an excellent match of rupture fronts in the simulations, with a discrepancy of less than 1 s
 516 in local rupture time. The first simulated earthquake initiates within the forced nucleation zone
 517 and propagates outward through the rest of the VW region over a period of ~ 30 s. The suite of
 518 simulations with a grid spacing of 1000 m includes two volume-discretized codes. While the discrepancy
 519 in rupture times increases to a few seconds among all codes, the qualitative rupture pattern is unchanged
 520 in the coarser-resolution simulations.

521 **4.1.2 Long-term Fault Behavior**

522 We then assess the long-term fault behavior, in terms of maximum slip rates over the seismogenic
 523 fault areas, in simulations with different resolutions (Figure 5). The simulations with a 1000 m
 524 grid spacing come from a wider range of codes and show similar features of earthquake recurrence
 525 and interseismic periods, with fault slip rates varying between $\sim 10^{-9}$ and 1 m/s. Since the spatial
 526 model resolution is suboptimal, the simulations show a large variability in the transient aseismic
 527 slip between large earthquakes. These transient features are completely absent in simulations with a
 528 500 m grid spacing and hence are numerical artifacts, rather than physical features. We also notice
 529 a persistent discrepancy of large event recurrence intervals even among better resolved simulations.

530 The computational demand of 3D benchmark problems prohibits a comprehensive self-convergence
 531 test of all participating numerical codes. We use the SBEM simulations (`lambert`) to demonstrate
 532 that self-convergence of simulation results may not show the true solution of the mathematically
 533 defined benchmark problems, when the domain size is not sufficiently large. In Figure 6, we show
 534 simulations with a range of grid spacings (125, 250, 500, and 1000 m) and three computational
 535 domain sizes: (120 km, 90 km), (240 km, 180 km), and (480 km, 360 km) for the along-strike and
 536 along-dip model dimensions, denoted as S1, S2, and S3, respectively.

537 The comparison of these simulations using the same code suggests some challenges in assessing
 538 model agreement in 3D problems. First, with a smaller computational domain size (S1), simulations
 539 appear to converge to a similar pattern of long-term behavior (Figure 6a–b). However, when the
 540 computational domain size is increased (S2 and S3), the simulations produce different earthquake

541 patterns, with alternating nucleation locations (Figure 6c–d). This difference results in a minor,
 542 though noticeable, change in the recurrence time of subsequent events. The sensitivity of nucleation
 543 location in BP4-QD likely results from the spatially uniform frictional properties and near-symmetric
 544 stress field associated with the fault-spanning quasi-dynamic earthquake ruptures. Even though we
 545 are approaching the computational limit, we expect that model behavior will presumably stabilize
 546 and converge to the same pattern as domain size substantially increases, as we have seen in 2D
 547 problems (*Erickson et al., 2020*).

548 **4.2 Half-Space Problem BP5-QD**

549 **4.2.1 Initial Rupture Propagation**

550 The rupture fronts of the first event in BP5-QD simulations show an excellent agreement with
 551 each other, with slightly increased discrepancy compared with BP4-QD results (Figure 4). The
 552 simulated earthquake rupture propagates into the transition zones around the VW region and reaches
 553 the surface, with the total rupture lasting over 30 s. The maximum discrepancy in local rupture
 554 time is less than two seconds among most simulations, and a few seconds between the EQsimu
 555 simulation and others, with the former showing higher rupture speeds.

556 When we use a lower threshold slip rate, $V_{th} = 0.03$ m/s, to determine the coseismic phase, the
 557 rupture front contours appear more discrepant, though retaining a qualitative agreement among
 558 simulations (Figure 7a). This alternative comparison reveals a large variability in the evolution
 559 of slower slip preceding the earthquake rupture among simulations. Increased discrepancies are
 560 found among SBEM/BEM simulations, while the largest discrepancies are associated with the two
 561 volume-discretized codes, which seem to produce rupture speeds that are either higher or lower
 562 than the average values among the group. Nonetheless, a smaller grid spacing helps reduce the
 563 differences in rupture fronts between EQsimu and other simulations, albeit at an increased computational
 564 expense (Figure 7b).

565 **4.2.2 Long-Term Fault Behavior**

566 We first show the overall earthquake patterns in BP5-QD (Figure 8). We juxtapose the profiles
 567 of fault slip partitioning in the along-strike and along-depth directions from two codes, FDRA and
 568 BICycle, based on BEM and SBEM methods, respectively. The results show that, following the
 569 first earthquake, later events exhibit recurrent slip patterns. The coseismic slip occurs within the
 570 VW region and into the shallow VS region, whereas postseismic and interseismic slip occurs in the
 571 adjacent VS regions and to a lesser extent near the surface. In contrast to BP4-QD, these BP5-QD
 572 simulations have a persistent location for earthquake initiation due to the heterogeneity in frictional
 573 properties that we introduced in this benchmark.

574 We found overall good agreements of maximum slip rates over the seismogenic fault areas
 575 among simulations with the suggested resolutions ($\Delta x = 1000$ m) (Figure 9a). The inter-event times
 576 of simulated earthquakes vary around ~ 235 years over the 1800-year simulation period. A small
 577 yet persistent difference in recurrence intervals can lead to apparent divergent timing of large events
 578 in simulations, especially for the EQsimu simulation, which appears to be affected by some pre-event
 579 aseismic transients. Despite the minor discrepancy in rupture fronts shown earlier, the total rupture
 580 duration and stress drop of the first event match closely among simulations for which catalog data
 581 are available (Figure 9b-c). We determine the beginning and end of the coseismic period as the
 582 moment any point on the fault reaches above or all points drop below a threshold slip rate of 0.1
 583 m/s, respectively, to be consistent with how we estimate the rupture time in Figure 4. The simulated
 584 earthquakes have robust characteristics, with rupture durations of ~ 30 s and stress drops of ~ 5
 585 MPa.

586 We then examine the time evolution of local slip rates and shear stress on the fault, at the
 587 surface ($x_3 = 0$ km) and the mid-seismogenic depth ($x_3 = 10$ km), during the first 1000 years of
 588 BP5-QD simulations (Figures 10 and 11). The periodic variations in local shear stress and slip
 589 rates are distinct at different depths. At the surface, large coseismic strength drops are accompanied
 590 with small stress drops due to the VS properties of the near-surface layer (Figure 10). In contrast,
 591 substantial coseismic stress drops occur within the VW region during earthquakes followed by
 592 interseismic strain buildup, leading to slip rate variations over tens of orders of magnitude (Figure 11).
 593 We observe a slightly larger discrepancy between simulations at depth than at the surface. Despite
 594 noticeable differences in earthquake recurrence times, all simulations accurately capture the full
 595 range of slip rate and stress variations. While simulations performed at the suggested resolution
 596 ($\Delta x = 1000$ m) already show good agreements in terms of the long-term fault behavior, a smaller
 597 grid spacing ($\Delta x = 500$ m) further improves the results.

598 **4.2.3 Coseismic Rupture and Off-Fault Behavior**

599 The comparisons of individual earthquake ruptures reveal high consistency among different
 600 simulations, as well as some complexity in the development and location of earthquake nucleation
 601 processes. In Figure 12, we show the time evolution of shear stress and slip rate at three representative
 602 locations: within the forced nucleation zone ($x_2 = -24$ km, $x_3 = 10$ km), at the surface ($x_2 = x_3 = 0$ km),
 603 and within the rupture propagation zone ($x_2 = 0$ km, $x_3 = 10$ km) during the first event in the sequence.
 604 All time series data are aligned relative to the earthquake initiation time (defined with a threshold
 605 slip rate $V_{\text{th}} = 0.1$ m/s) in each simulation. Consistent with Figure 4, all simulations show a good
 606 agreement in coseismic slip rate and stress evolution, with some minor differences in peak slip
 607 rates.

608 For the simulated fourth event, we found slightly increased model discrepancies, due to subtle
 609 differences in the earthquake nucleation condition resulting from the prior slip history (Figure 13).
 610 While most simulations retain the same source evolution function, the results from two simulations
 611 with TriBIE and EQsimu appear qualitatively different over much of the seismogenic zone. This
 612 pronounced difference is due to the different initiation locations of the earthquake. Since the nucleation
 613 zone in BP5-QD has a large size, the majority of the deeper VW zone hosts aseismic slip. These
 614 areas can serve as alternative locations to start an earthquake, when the local stress conditions
 615 below the central VW zone outcompete the favorable nucleation zone in our benchmark design.
 616 When we compare simulations with a halved grid spacing of 500 m, the variability of nucleation
 617 location in TriBIE and EQsimu simulations disappears. The distinct behavior of these simulations
 618 based on BEM and FEM methods suggests that the earthquake nucleation in this benchmark is still
 619 susceptible to the specific setup of a computational model.

620 To further assess model convergence, we compare the sixth event in simulations with smaller
 621 grid spacings of 500 and 250 m (Figure 14). Simulations with a grid spacing of 500 m show excellent
 622 agreements. However, we notice emergent complexity in BICycle simulations that indicates a
 623 different nucleation location of the sixth event. Similar to the aforementioned results about TriBIE
 624 and EQsimu, we find that earthquake nucleation in finer-resolution simulations (250 m) with BICycle
 625 return to the same location that matches other simulations. In spite of such variability in a few
 626 simulations, the clear improvements in model agreement suggest that different numerical codes
 627 will likely converge to well-resolved physical behavior with a decrease in the grid spacing.

628 We also compare the off-fault behavior of simulation groups where these outputs are available
 629 (Figure 15). Note that most simulations explicitly solve for off-fault responses, except for the case
 630 of BICycle (Lambert), where off-fault displacements are calculated using previously simulated
 631 fault slip history and semi-analytical Green's functions (Okada, 1992). For codes Unicycle and
 632 TriBIE, off-fault displacements are calculated in the simulations using Okada Green's functions for
 633 only fault patches in the frictional domain, excluding deep-seated displacement. For a consistent
 634 comparison with other simulations, we add long-term displacement trend to off-fault time series
 635 from Unicycle and TriBIE simulations using $V(x_1) = V_L/\pi \cdot \arctan(x_1/H)$ (Savage and Burford,
 636 1973), where $H = 18$ km.

637 Focusing on the first and fourth event, we observe a good qualitative agreement of surface
 638 velocity time series at various distances away from the fault, with the later (fourth) event more
 639 challenging to match (Figure 15a–b). Overall, the discrepancies in coseismic slip rate evolution
 640 appear larger than all the on-fault properties that we examined. This is likely due to multiple factors,
 641 including inaccurate representations of surface observation points (grid points offset from the surface)
 642 and domain truncation in the fault-normal direction. The long-term displacement history at these
 643 off-fault locations also yield good qualitative agreements (Figure 15c).

644 **4.2.4 Model Discrepancy and Convergence**

645 From previous comparisons, we observe that long-term model observables such as recurrence
646 intervals appear more variable than short-term earthquake characteristics such as coseismic slip
647 and stress drop. To better understand the long-term divergence of simulation results, we explore the
648 interseismic stressing history and its relationship with earthquake recurrence intervals (Figure 16).
649 We first calculate the changes in shear stress within the seismogenic zone in the postseismic and
650 interseismic period leading up to the sixth event. The mid-seismogenic stressing history features
651 higher positive stressing in the early postseismic period due to decaying afterslip, followed by increasing
652 positive stressing in the later interseismic period and negative stressing as the creep fronts enter
653 the seismogenic zone. We can estimate the minimum stressing rate (in insets of Figure 16a and c)
654 when the postseismic period transitions to the interseismic period. This minimum stressing rate is
655 well-defined and less susceptible to the complex fault slip history, hence reflecting differences in
656 large-scale, long-term loading in each simulation.

657 In both simulation groups using grid spacings of 1000 and 500 m, we found that the minimum
658 interseismic stressing rate is approximately inversely correlated with the nearly constant recurrence
659 intervals of large events (Figure 16b and d). This minimum stressing rates in volume-discretized
660 codes EQsimu and GARNET tend to deviate from the cluster of SBEM/BEM results, although
661 the general relationship between interseismic stressing rates and recurrence intervals still holds.
662 The subsequent stressing history appear more variable among many simulations, especially in
663 cases with a grid spacing of 500 m, indicating the complexity in aseismic slip evolution. These
664 comparisons suggest that stress buildup process is essentially similar across simulations and explain
665 why these simulations have more robust earthquake characteristics, even in the presence of growing
666 discrepancies in the long term.

667 We then characterize the convergence of these simulations with different resolutions, in terms
668 of three observables of simulated earthquakes (Figure 17). We plot the total rupture duration, and
669 final slip and peak slip rate at the center of the VW region ($x_2 = 0$ km; $x_3 = 10$ km) during the first
670 and sixth events, because these quantities capture the overall or local properties of earthquake ruptures.
671 We have included BEM/SBEM simulations with resolutions from 2000 m down to 250 m, and
672 FEM/FDM simulations with a smallest grid spacing of 500 or 1000 m. We found a better agreement
673 in these observables for the first event than the sixth event and a closer match in simulations with
674 smaller grid spacings, consistent with our earlier results (Figures 4, 12, and 14). As the convergence
675 test of simulations are not always computationally feasible for these 3D problems, these comparisons
676 provide an alternative approach to verify the involved numerical codes.

677 5 Discussions

678 5.1 Important Computational and Physical Factors

679 The choice of computational domain size has a major influence on simulation results, often
 680 in concert with other computational factors such as grid spacing and boundary conditions. The
 681 comparisons of global fault properties in BP4-QD (Figures 5 and 6) demonstrate that simulations
 682 with a specific code (BICycle) can robustly produce certain earthquake patterns and characteristics
 683 with a decreasing grid spacing. However, the apparent self-converging behaviors are associated
 684 with specific domain sizes. The differences between these cases imply that the adopted domain
 685 sizes are not sufficiently large to solve the semi-infinite domain problem. The model discrepancy
 686 persists due to the variability of earthquake nucleation locations, even when we adequately resolve
 687 the cohesive zone during rupture propagation with a grid spacing of 125, 250 and 500 m. These
 688 results for BP4-QD suggest that domain truncation prevents simulations from converging toward
 689 the solution to the semi-infinite domain problem, at least with current computational resources.

690 Improvements in benchmark design can at least mitigate some complicating factors. In BP5-QD,
 691 we introduced persistent frictional heterogeneity to promote earthquake initiation at the same locations,
 692 thereby largely eliminating a key contributor to model discrepancies. The excellent agreement
 693 among simulated earthquake properties (Figure 17) further suggest that some model observables
 694 are less sensitive to computational factors such as the domain size.

695 The rupture front contours are diagnostic of rupture behavior and hence a key metric for model
 696 agreement, as noted for single-event dynamic rupture simulations (*Barall and Harris, 2014; Harris*
 697 *et al., 2009*). In SEAS simulations, we found various factors that lead to large discrepancies in
 698 rupture fronts even during the first event. Some factors are fixable issues, such as inaccurate or
 699 inconsistent model setup and parameter choices (Section 3). Some factors can be mitigated in
 700 improved benchmark design. For example, when revising BP5-QD, we increased the elevated
 701 initial slip rate, V_i , in the forced nucleation zone from 0.01 m/s to 0.03 m/s. This change shortens
 702 the period of pre-rupture stress buildup that turn out to be sensitive to the domain size, and improves
 703 agreement of the first earthquake.

704 Other issues represent inherent challenges in resolving the physical problem, e.g., when the
 705 free surface is involved. The comparison between BP4-QD and BP5-QD simulations with a grid
 706 spacing of 500 m (Figures 4a and 7b) suggests that the presence of the free surface and its interaction
 707 with earthquake rupture contribute to increased model discrepancies, even though the cohesive
 708 zone is better resolved in BP5-QD. Since we do not have simulations for the exact BP5-QD model
 709 setup in both whole space and half-space, we cannot directly characterize the effect of the free
 710 surface on 3D benchmark results.

711 **5.2 From 2D to 3D Benchmarks**

712 The experience and findings from our code verification exercises for 2D SEAS benchmarks
 713 (*Erickson et al., 2020*) are indispensable for code comparisons of 3D SEAS models. Strict self-convergence
 714 tests are often feasible in 2D problems, allowing us to comprehensively explore how suboptimal
 715 choices of computational domain size and model resolution can affect earthquake recurrence intervals
 716 and event statistics. The findings from 2D benchmarks hence serve as essential reference examples
 717 when we grapple with the effects of various computational factors in challenging 3D problems.

718 Benchmark problems in 3D have several unique features. First, the complexities of benchmark
 719 problems and consideration of computational constraints motivate the design of verification methods
 720 and metrics that reveal the relative sensitivities of different model observables. Specifically, earthquake
 721 rupture characteristics such as rupture duration, final slip, and peak slip rate appear to be more
 722 robust than other longer-term observables such as recurrence intervals and nucleation phase, because
 723 domain-size-dependent loading can substantially affect the timing of aseismic slip evolution. Additionally,
 724 global fault properties are more robust than local fault behavior, as expected. Second, the 3D nature
 725 of the problem brings new physical complexity, in particular the multiple potential locations for
 726 earthquake nucleation, compared with the single downdip nucleation location in 2D antiplane
 727 problem (*Erickson et al., 2020*). The interactions of stress heterogeneity and frictional properties
 728 throughout the fault slip history ultimately control earthquake nucleation, which cannot be chosen *a*
 729 *priori* by modelers. Third, the 3D setting and the presence of a free surface enables a direct comparison
 730 of model results and more complicated geophysical observations, which is important for the efforts
 731 to potentially validate SEAS models.

732 We highlight a few important outcomes of our code comparison results in connections to our
 733 2D exercises. First, excellent quantitative agreements in key model observables can be achieved
 734 with proper numerical resolution among different modeling group. Second, at marginal resolutions,
 735 several factors combine to affect model agreements and convergence. For this reason, we find generally
 736 larger discrepancies among the earthquake ruptures of 3D SEAS simulations than those in 2D
 737 SEAS and 3D single-event dynamic rupture simulations. Third, even in well-resolved models,
 738 long-term model observables are more sensitive than earthquake observables to minor differences
 739 in computational factors.

740 **5.3 Implications for Model Validation**

741 Our successful code comparison exercises lend confidence to the accuracy of the participating
 742 numerical codes, serving as an essential step towards the goal of creating valid, physics-based
 743 models for earthquake source processes. In our benchmarks, many simulated physical quantities
 744 can be measured or inferred with geological and geophysical methods covering distinct temporal

745 and/or spatial scales, such as seismograms, Global Navigation Satellite System (GNSS), satellite
746 imagery, and paleoseismic records, offering opportunities to compare SEAS models with diverse
747 observations. Furthermore, our efforts to understand how sensitive and variable model observables
748 are to both computational and physical factors also contribute to quantifying and reducing uncertainty
749 in the data-model integration. Ultimately, SEAS models validated with real-world observations and
750 through testable predictions can contribute to evaluating the hazard scenarios of past and potential
751 future earthquakes.

752 Despite computational challenges, the SEAS modeling framework presented here rigorously
753 resolves the important temporal and spatial scales in earthquake source processes, in ways that are
754 complimentary to and synergistic with dynamic rupture simulations and earthquake simulators. On
755 the one hand, the computational rigor and realistic physical processes in SEAS modeling can help
756 inform and improve the choices of procedures and parameterization, and approximation of physics
757 in other modeling frameworks. Examples include the design of self-consistent pre-rupture stress
758 conditions, and assessing the role of transient slow slip in time-dependent hazard. On the other
759 hand, the capabilities of other modeling approaches to connect with additional observations can
760 also improve the design of and help validate SEAS models.

761 **6 Conclusions**

762 We present code comparison results for 3D models of earthquake sequences and aseismic
763 slip from two recent benchmarks in the SEAS initiative (*Erickson et al., 2020*). The increased
764 complexity and computational cost of 3D SEAS problems motivate us to adopt new strategies
765 for benchmark design and code verification using a range of simulation outputs. We assess the
766 contours of coseismic rupture fronts, time series of fault slip, slip rates, and shear stress, time series
767 of off-fault displacement and velocity, and history of maximum fault slip rates, as well as earthquake
768 catalogs, from tens of simulations contributed by 10 modeling groups.

769 We achieve excellent model agreements among most outputs and observables with relatively
770 large computational domain size, although discrepancies are slightly larger than those in 3D single-event
771 dynamic rupture and 2D SEAS simulations, partly due to spatial resolutions limited by the computational
772 cost. The successful code verification exercises lend confidence to the accuracy of participating
773 numerical codes. The quantitative differences of simulation results depend on computational factors
774 such as model domain size, grid discretization and spacing, and boundary conditions. Coseismic
775 observables appear more robust than longer-term, aseismic observables that are more easily influenced
776 by domain-size-dependent loading. Understanding the causes of model discrepancies and relative
777 sensitivities of various model observables are important, as researchers work towards integrating
778 the outputs of numerical simulations with the increasing volumes of geological and geophysical
779 observations.

780 The earthquake problem is a prime example of a dynamic solid-Earth system that span wide-ranging
 781 time and space scales. Our community-driven code verification efforts are aimed at improving and
 782 promoting a new generation of rigorous, robust numerical codes for earthquake science. Our results
 783 and lessons could be useful to other research areas that involve numerical simulations of nonlinear,
 784 multi-scale dynamic problems.

785 **Open Research**

786 Our online platform (<https://strike.scec.org/cvws/seas/>) hosts the simulation data
 787 for local and global fault properties and rupture times. The descriptions of benchmarks BP4 and
 788 BP5 are available at <https://strike.scec.org/cvws/seas/download/> (SEAS_BP4_QD.pdf
 789 and SEAS_BP5.pdf) and included as supplementary materials. See the references in Table 2 for
 790 the availability of numerical codes. Code GARNET is available at [https://bitbucket.org/
 791 cpranger/garnet](https://bitbucket.org/cpranger/garnet).

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 796 J.J. analyzed all simulation results and led the writing of the manuscript. All remaining authors
 797 provided feedback on benchmark design, participated in the benchmark exercises (listed in Table 2),
 798 and/or helped with revising the manuscript. V.L. additionally helped with the early tests of benchmark
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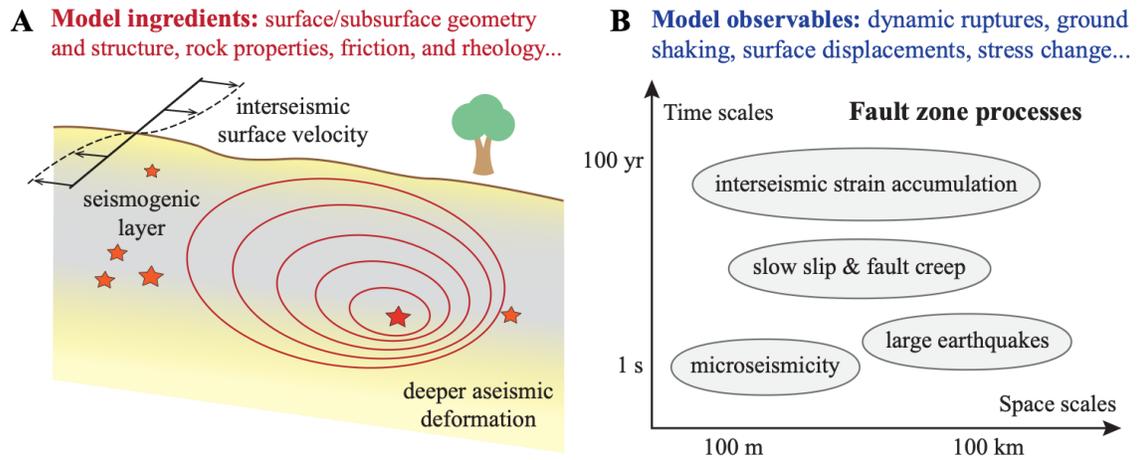


Figure 1. Main ingredients and observables in 3D models of sequences of earthquakes and aseismic slip (SEAS).

(a) In a conceptual model of a strike-slip fault zone subject to long-term tectonic plate loading, microseismicity and large earthquakes (hypocenters denoted by red stars) initiate at depths, and large events propagate (rupture front contours in red) through the seismogenic layer (gray), whereas aseismic motion occurs in deeper and sometimes shallower regions (yellow). (b) The space and time scales associated with diverse fault zone processes that can be reproduced in 3D SEAS models. The observables of these processes include interseismic strain accumulation, slow slip, fault creep, dynamic ruptures of microseismicity and large earthquakes, and associated ground shaking and deformation.

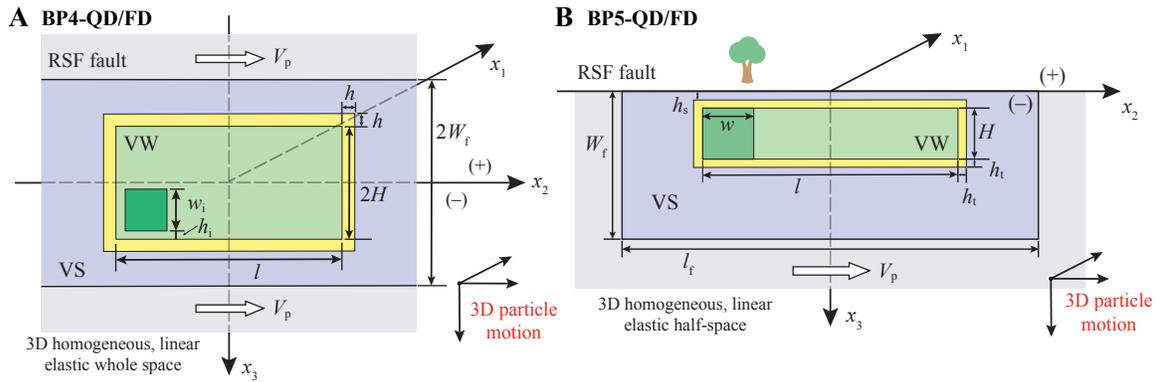


Figure 2. Two benchmark problems for 3D SEAS models. The benchmarks (a) BP4 and (b) BP5 consider 3D motion with a vertical planar fault embedded in a homogeneous, isotropic, linear elastic whole space and a half-space with a free surface, respectively. The fault is governed by a rate-and-state friction (RSF) law in the central region (non-gray colors) with a size of $(\infty, 2W_f)$ for PB4 and (l_f, W_f) for BP5, and creeps at an imposed constant plate loading rate at the boundaries (gray). The velocity-weakening region (light and dark green), with a size of $(l, 2H)$ for BP4 and (l, H) for BP5, is surrounded by a transition zone (yellow) and velocity-strengthening regions (blue). The initial nucleation zone (dark green square) is located at one end of the velocity-weakening region. Earthquakes spontaneously nucleate and propagate across the seismogenic fault.

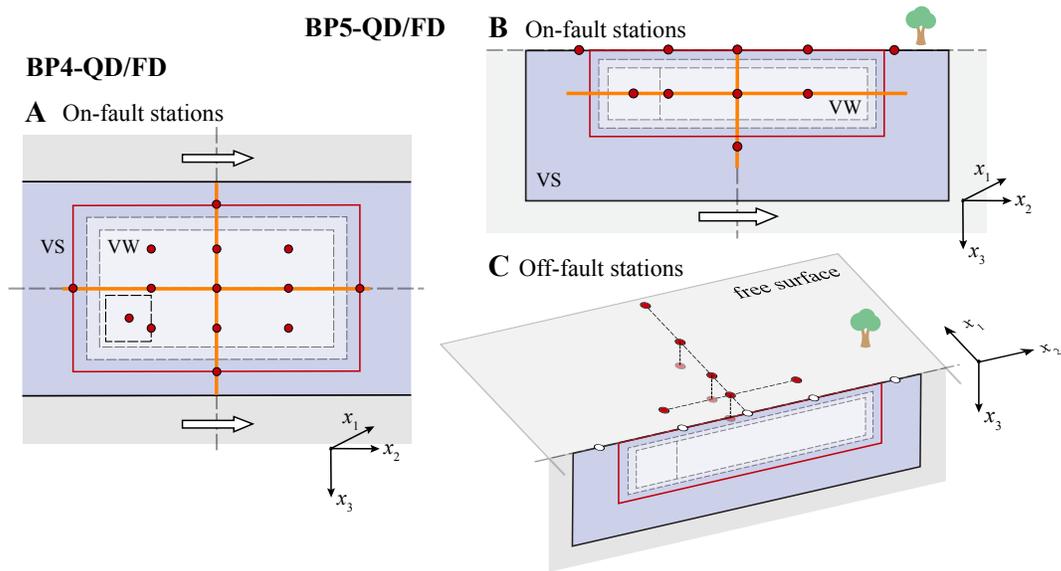


Figure 3. Simulation outputs for 3D SEAS benchmarks. Observation points, lines, and areas are shown for (a) BP4 and (b and c) BP5. Local time series is produced at (a and b) on-fault and (c) off-fault points (red). Slip and stress evolution profiles are produced along cross-section lines (orange). The region outlined in red is considered in estimating time-dependent source properties and rupture front contours. Dashed rectangles indicate fault areas with different frictional properties.

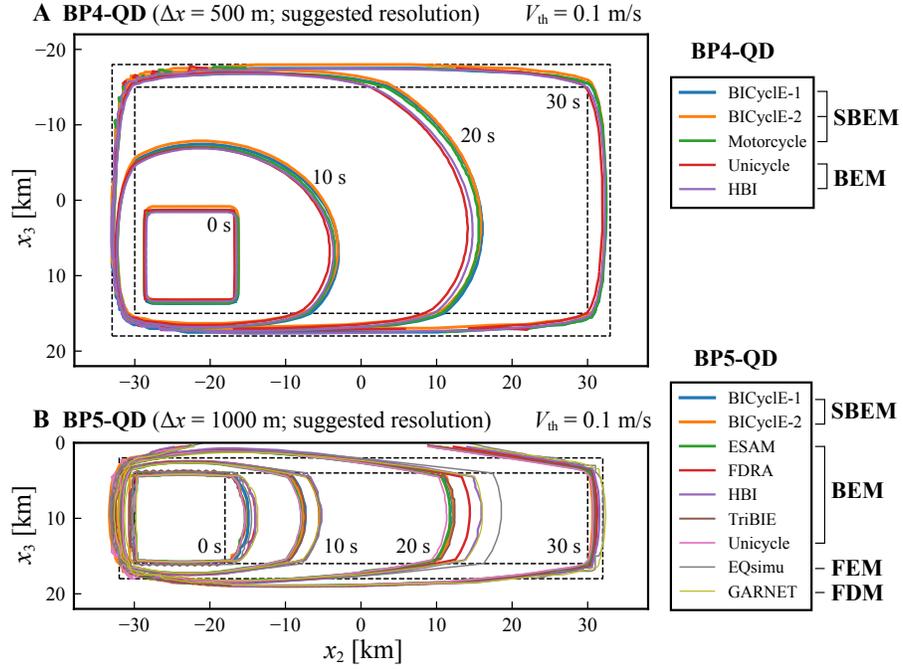


Figure 4. Rupture fronts of the first earthquake in BP4-QD and BP5-QD simulations with suggested numerical resolutions. The contours of rupture fronts are shown for simulations in (a) BP4-QD ($\Delta x = 500$ m) and (b) BP5-QD ($\Delta x = 1000$ m). The rupture front contours indicate 0, 10, 20, and 30 s after the earthquake initiation time, defined as the moment any point on the fault reaches a threshold slip rate $V_{th} = 0.1$ m/s. The legends show code names and corresponding types of numerical methods listed in Table 2. BICycle-1 and BICycle-2 refer to simulations from jiang and lambert, respectively.

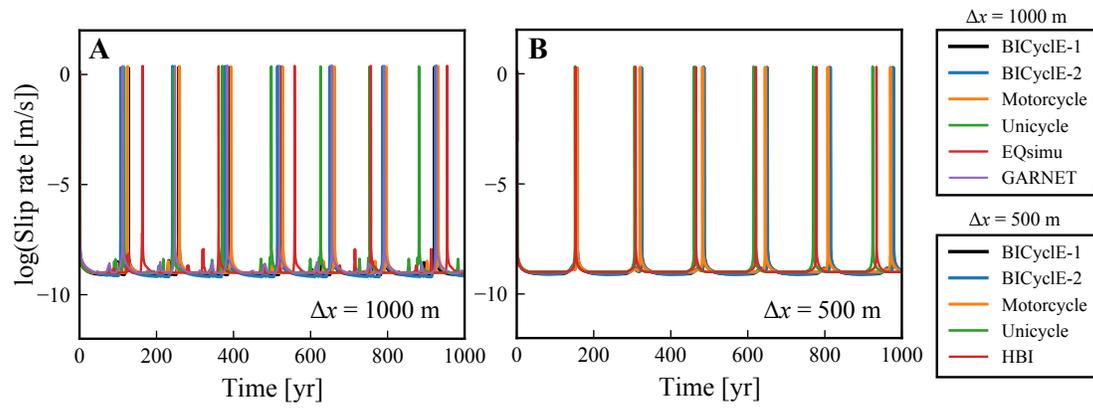


Figure 5. Time evolution of maximum slip rates in BP4-QD simulations. The time series of logarithmic maximum slip rates within the seismogenic zone are shown for simulations with (a) $\Delta x = 1000$ m and (b) $\Delta x = 500$ m. Logarithms with base 10 are shown in this and all later figures. Legend labels show code names in this and all later figures.

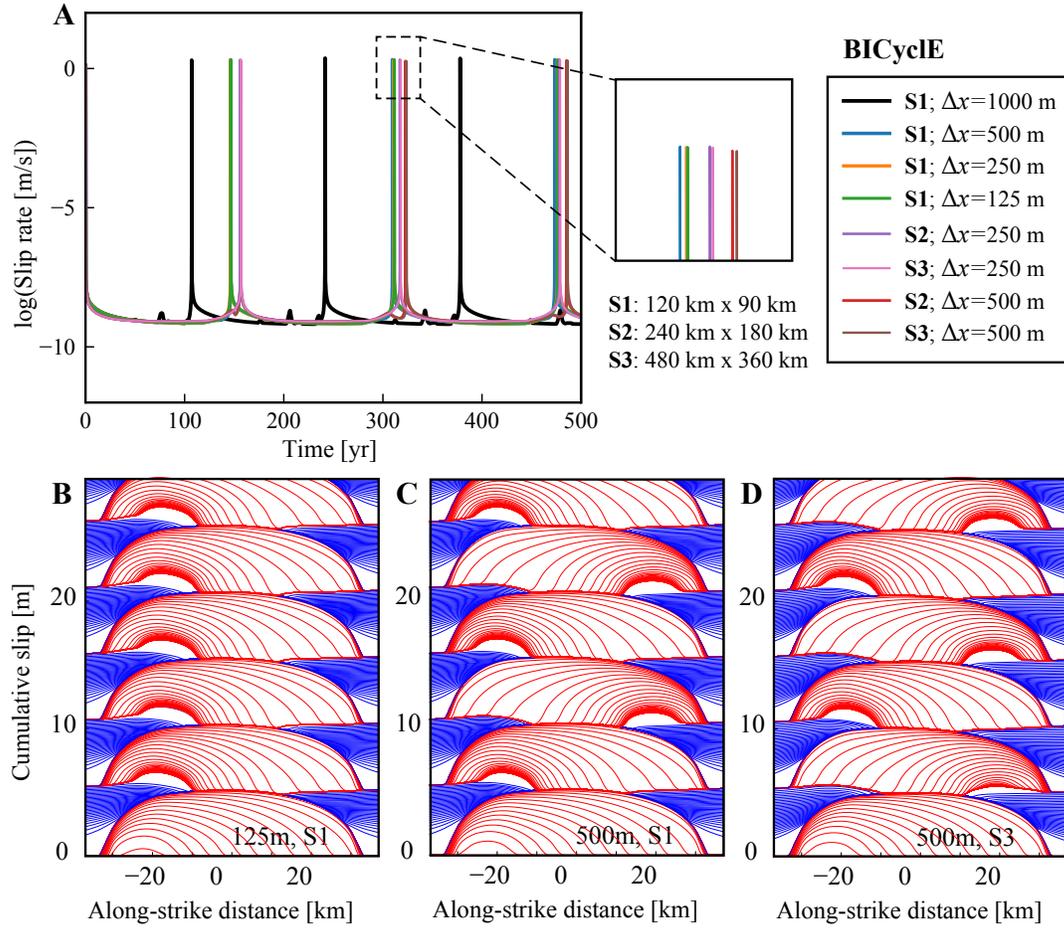


Figure 6. Effect of computational grid spacing and domain size on the self-convergence of SBEM simulations. (a) Time evolution of maximum slip rates for a suite of SBEM simulations with different grid spacings ($\Delta x = 125, 250, 500,$ and 1000 m) and domain sizes: $(L_2, L_3) = (120 \text{ km}, 90 \text{ km}), (240 \text{ km}, 180 \text{ km}),$ or $(480 \text{ km}, 360 \text{ km}),$ denoted as S1, S2, or S3, respectively. Cumulative slip in the along-strike direction is plotted every 2 s for the seismic period (red lines) and every 5 yr for the aseismic period (blue lines) in three simulations with (b) $\Delta x = 125$ m and S1; (c) $\Delta x = 500$ m and S1; and (d) $\Delta x = 500$ m and S3.

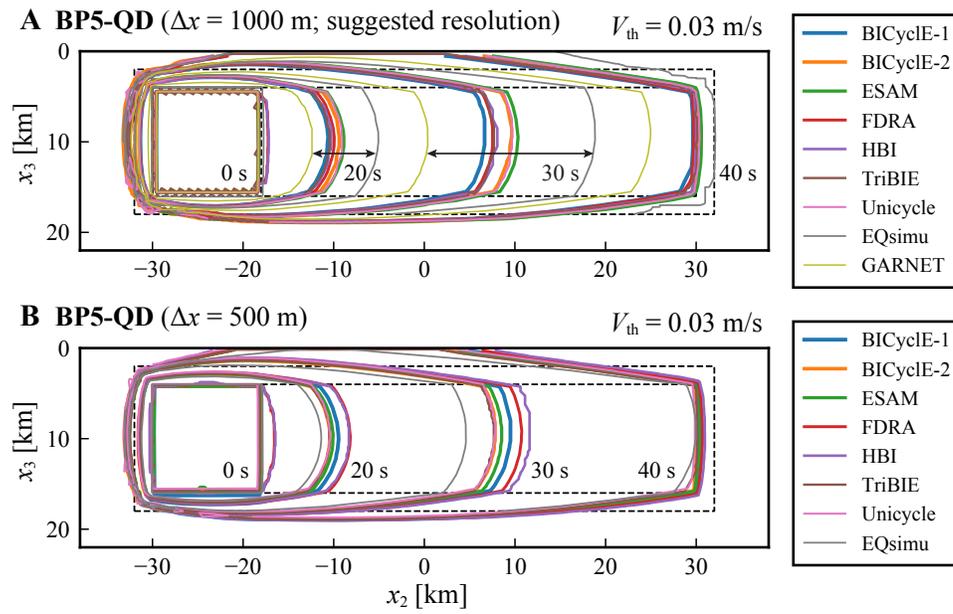


Figure 7. Rupture fronts of the first earthquake in BP5-QD simulations with different numerical resolutions. The contours of rupture fronts indicate 0, 20, 30, and 40 s after the earthquake initiation time in simulations with (a) $\Delta x = 1000$ m and (b) $\Delta x = 500$ m. The threshold slip rate for the coseismic phase, $V_{th} = 0.03$ m/s, is different from that in Figure 4.

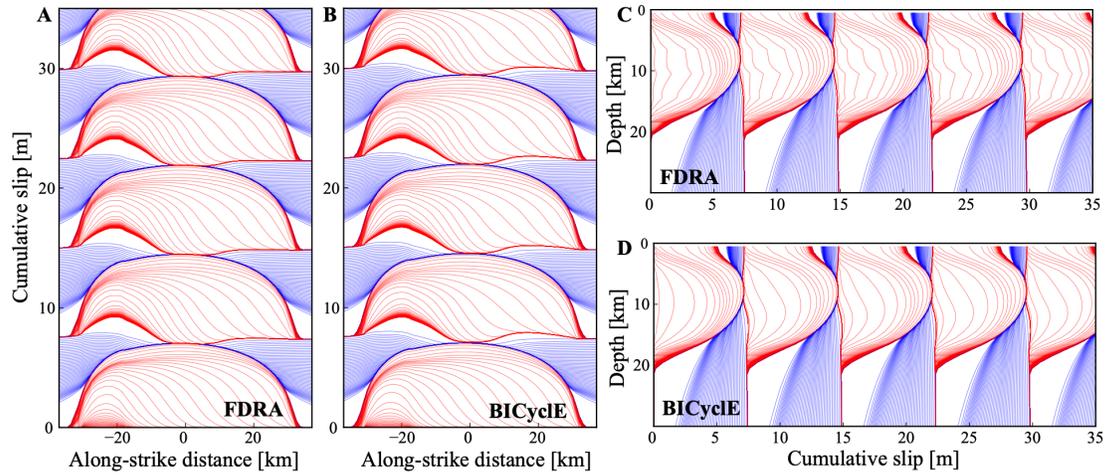


Figure 8. Fault slip evolution in selected BP5-QD simulations. Cumulative fault slip in two simulations ($\Delta x = 1000$ m) using FDRA and BICyclE are shown in the (a and b) along-strike and (c and d) along-depth directions. The seismic slip (red lines) is plotted every 2 s and aseismic slip (blues lines) is plotted every 5 yr. Note that downsampling and interpolation of simulation outputs in space and time sometimes affects visualization, such as panel c here.

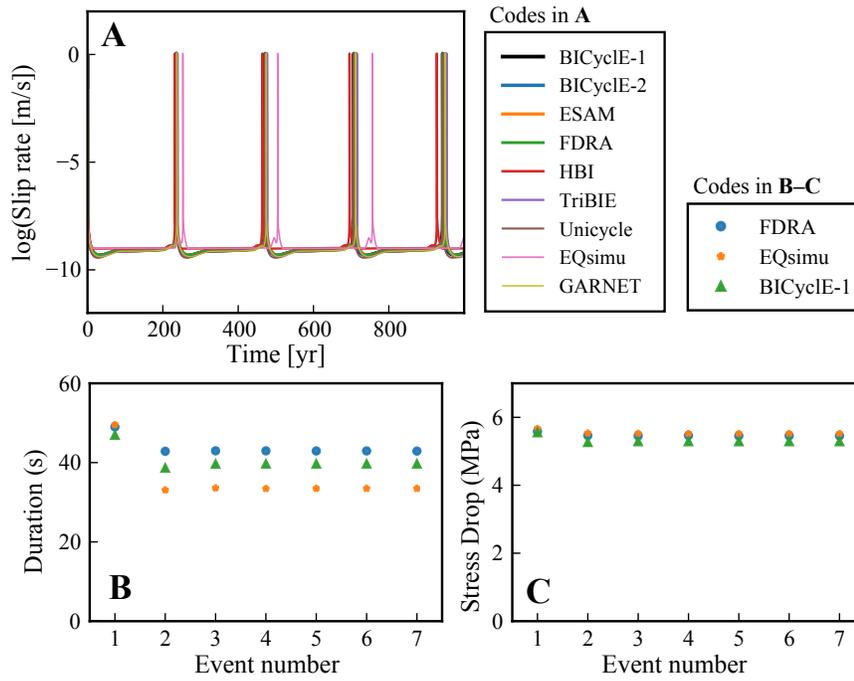


Figure 9. Long-term fault behavior and earthquake characteristics in BP5-QD simulations. (a) Time evolution of maximum slip rates in the seismogenic zone and (b) rupture duration and (c) stress drop for the first seven earthquakes are shown for simulations with $\Delta x = 1000$ m.

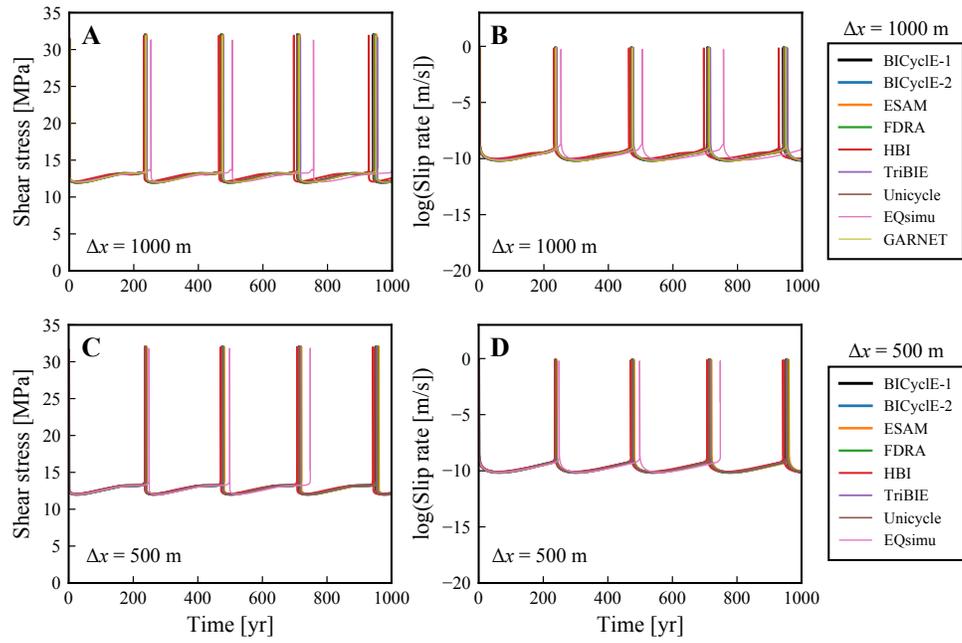


Figure 10. Long-term fault behavior at the surface in BP5-QD simulations. (a and c) Shear stress and (b and d) slip rates on the fault at the surface ($x_1 = x_2 = x_3 = 0$ km) in simulations with (a and b) $\Delta x = 1000$ m and (c and d) $\Delta x = 500$ m.

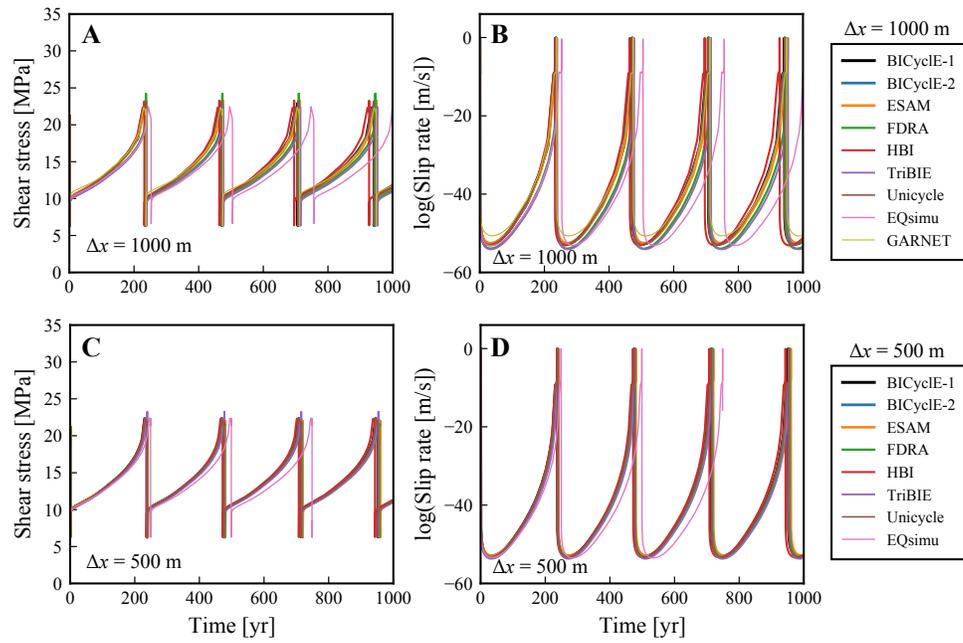


Figure 11. Long-term fault behavior at a seismogenic depth in BP5-QD simulations. (a and c) Shear stress and (b and d) slip rates on the fault at the mid-seismogenic depth ($x_1 = x_2 = 0$ km; $x_3 = 10$ km) in simulations with (a and b) $\Delta x = 1000$ m and (c and d) $\Delta x = 500$ m.

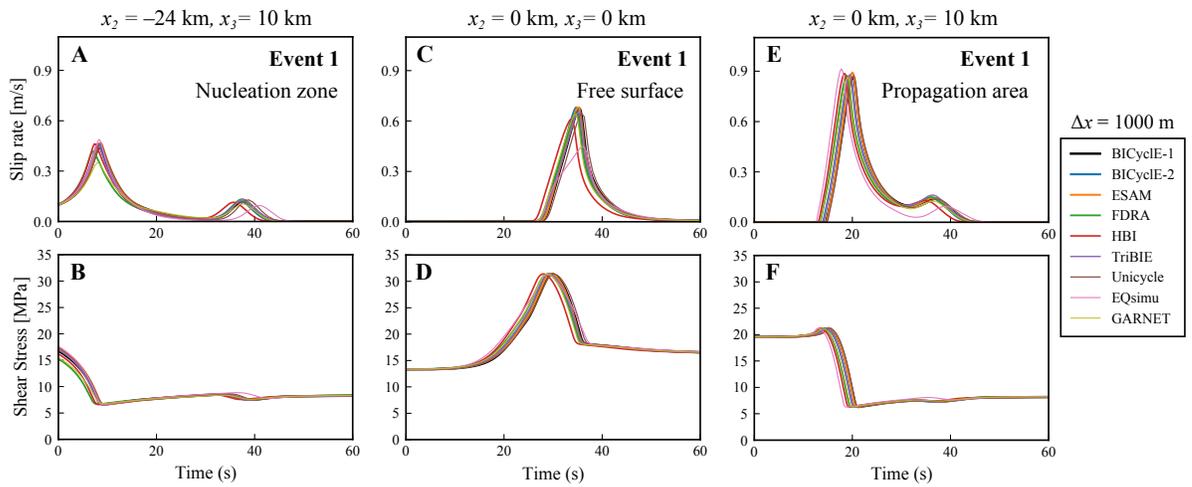


Figure 12. Coseismic rupture of the first event in BP5-QD simulations ($\Delta x = 1000$ m). Time evolution of (a, c, and e) slip rates and (b, d and f) shear stresses during the first earthquake are shown at different locations on the fault. Panels a and b refer to a point within the initial nucleation zone ($x_2 = -24$ km; $x_3 = 10$ km); c and d refer to a point at the free surface ($x_2 = 0$ km; $x_3 = 0$ km); e and f refer to a point within the propagation zone ($x_2 = 0$ km; $x_3 = 10$ km).

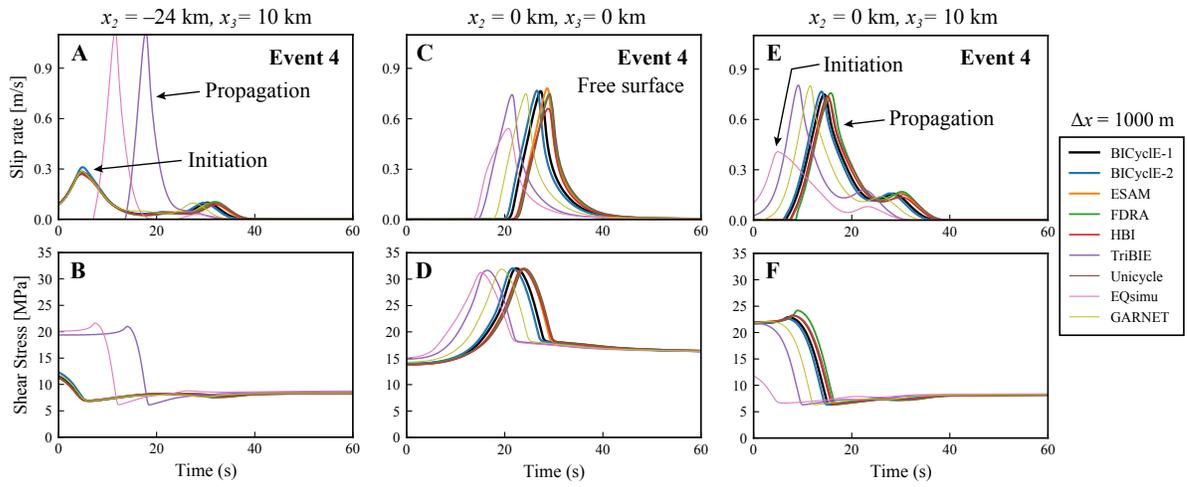


Figure 13. Coseismic rupture of the fourth event in BP5-QD simulations ($\Delta x = 1000$ m). Time evolution of (a, c, and e) coseismic slip rates and (b, d and f) shear stresses are shown at the same locations on the fault as in Figure 12.

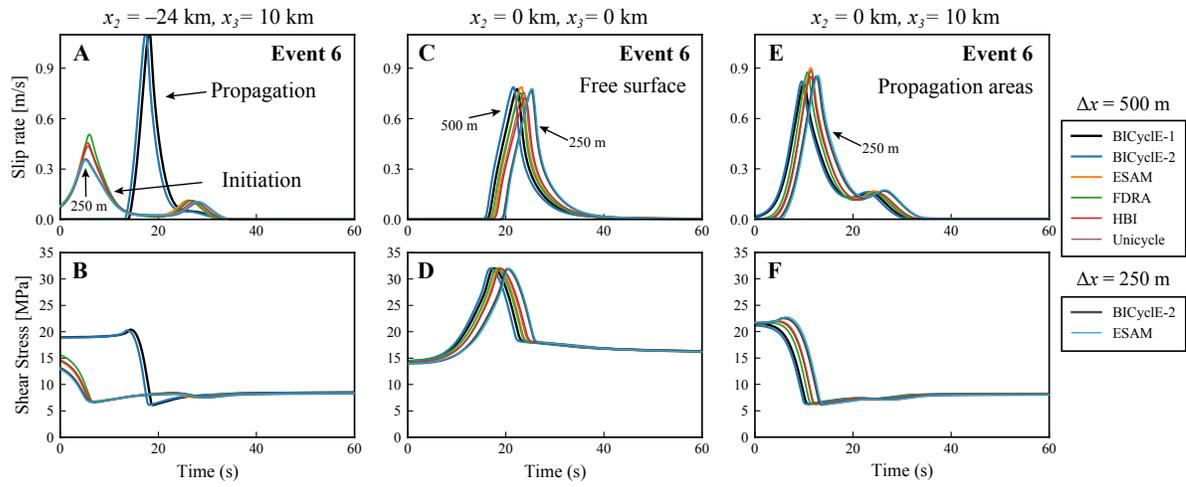


Figure 14. Coseismic rupture of the sixth event in BP5-QD simulations ($\Delta x = 500$ and 250 m). Time evolution of (a, c, and e) coseismic slip rates and (b, d and f) shear stresses are shown at the same locations on the fault as in Figure 12.

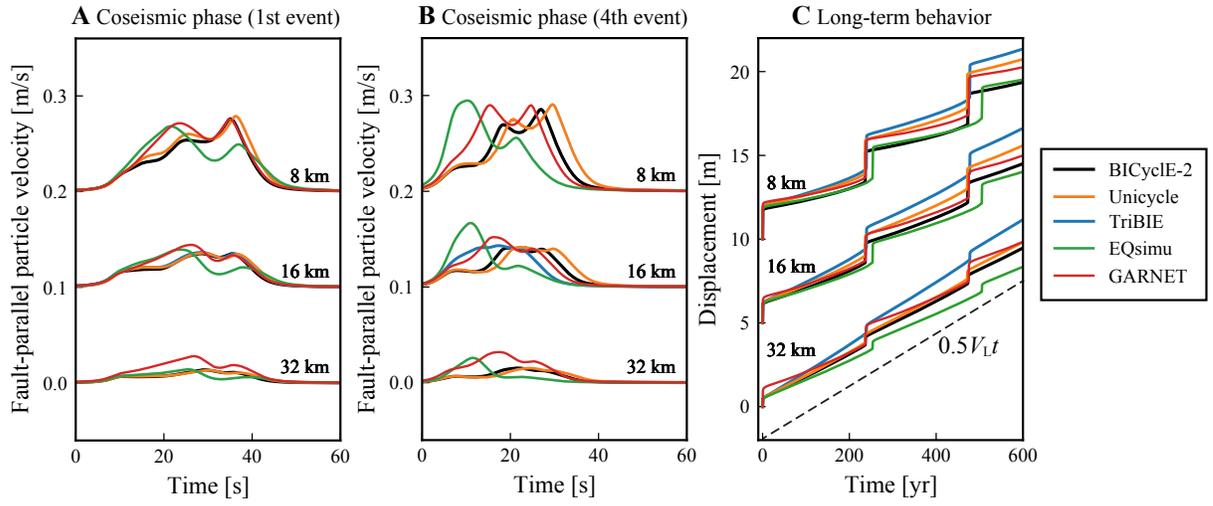


Figure 15. Off-fault ground movement in BP5-QD simulations. Fault-parallel displacement rates v_2 during the (a) first and (b) fourth events, and (c) long-term displacement history are shown at three off-fault locations on the surface ($x_1 = 8, 16,$ or 32 km; $x_2 = 0$ km; $x_3 = 0$ km). The dashed line indicates the far-field surface displacement $0.5V_L t$. The time series corresponding to different locations and the dashed line are vertically offset for visualization purpose.

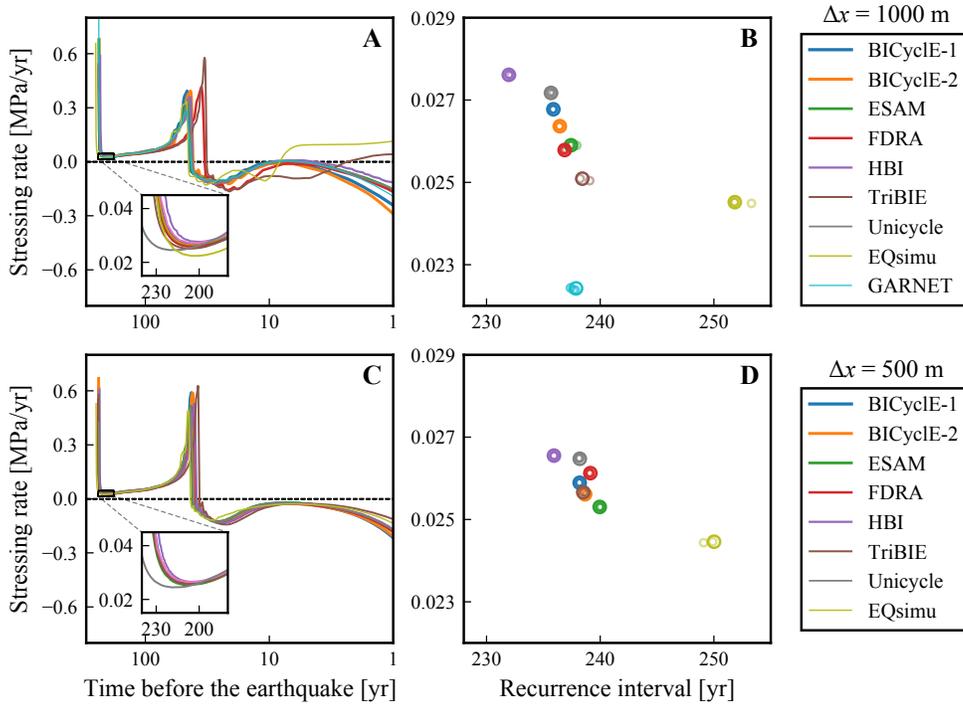


Figure 16. Interseismic stressing rate history and earthquake recurrence intervals in BP5-QD simulations. (a and c) Stressing rates at the mid-seismogenic depth ($x_2 = 0$ km; $x_3 = 10$ km) during the postseismic and interseismic periods before the sixth earthquake. (b and d) The minimum interseismic stressing rates (enlarged windows in a and c) and recurrence intervals are shown for the corresponding events (large circles in color) and preceding events (smaller circles in the same color). Simulations with $\Delta x = 1000$ m and $\Delta x = 500$ m are shown in panels a–b and c–d, respectively. Due to a shorter simulation time, the fourth event from TriBIE and EQsimu is considered in panels c–d.

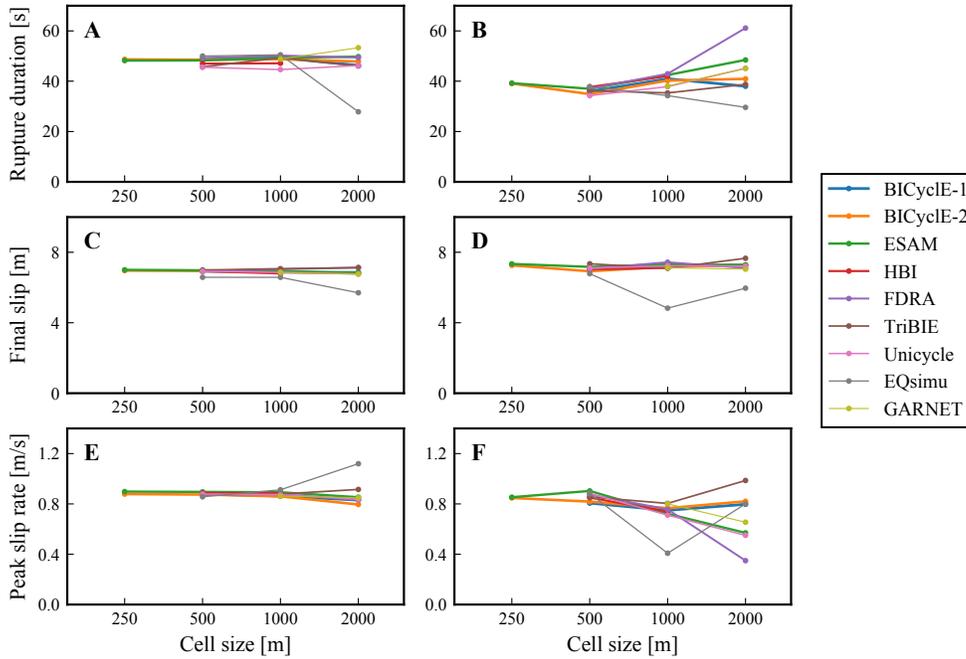


Figure 17. Comparison of earthquake characteristics in simulations with different resolutions. Coseismic rupture durations are shown for the (a) first and (b) sixth events in simulations with $\Delta x = 250, 500, 1000,$ and 2000 m, when available. (c and d) Coseismic slip and (e and f) peak slip rate at the mid-seismogenic depth ($x_2 = 0$ km; $x_3 = 10$ km) are shown for the (c and e) first and (d and f) sixth event, respectively. Note an exception that the fourth event from TriBIE and EQsimu is considered for $\Delta x = 500$ m in panels b, d, and f. Simulation results from each modeling group are plotted as line-connected dots.

Table 1. Parameters in benchmark problems BP4-QD and BP5-QD

Parameter	Definition	Value in BP4	Value in BP5
ρ	density	2670 kg/m ³	2670 kg/m ³
c_s	shear wave speed	3.464 km/s	3.464 km/s
ν	Poisson's ratio	0.25	0.25
σ_n	effective normal stress on fault	50 MPa	25 MPa
L	characteristic state evolution distance	0.008 m	0.14 m/0.13 m [†]
a_0	rate-and-state direct-effect parameter	0.0065	0.004
a_{\max}	rate-and-state direct-effect parameter	0.025	0.04
b_0	rate-and-state evolution-effect parameter	0.013	0.03
V_L	plate loading rate	10 ⁻⁹ m/s	10 ⁻⁹ m/s
V_{init}	initial slip rate	10 ⁻⁹ m/s	10 ⁻⁹ m/s
V_i	elevated initial slip rate	0.01 m/s	0.03 m/s
V_0	reference slip rate	10 ⁻⁶ m/s	10 ⁻⁶ m/s
f_0	reference friction coefficient	0.6	0.6
H	(half-)width of uniform VW region	15 km	12 km
l	length of uniform VW region	60 km	60 km
$h(h_t)$	width of VW-VS transition zone	3 km	2 km
h_s	width of shallow VS zone	-	2 km
W_f	(half-)width of rate-and-state fault	40 km	40 km
l_f	length of rate-and-state fault	-	100 km
Δz	suggested grid spacing	500 m	1000 m
t_f	final simulation time	1500 years	1800 years
w	width of favorable nucleation zone	12 km	12 km
Λ_0	quasi-static process zone size	2 km	6 km
h^*	nucleation zone size	12.4 km	12.5 km

† The value used in the favorable nucleation zone.

Table 2. Participating SEAS codes and modeling groups

Code Name	Type	Simulation [†] (Group Members)	BP4-QD	BP5-QD	Reference
BICycle	SBEM	jiang (Jiang)	✓	✓	<i>Lapusta and Liu (2009)</i>
		lambert (Lambert, Lapusta)	✓	✓	
Motorcycle	SBEM	barbot (Barbot)	✓		<i>Barbot (2021)</i>
ESAM	BEM	liu (Y. Liu)		✓	<i>Liu and Rice (2007)</i>
FDRA	BEM	cattania (Cattania)		✓	<i>Segall and Bradley (2012)</i>
HBI	BEM	ozawa (Ozawa, Ando)	✓	✓	<i>Ozawa et al. (2021)</i>
TriBIE	BEM	dli (D. Li)		✓	<i>Li and Liu (2016)</i>
Unicycle	BEM	barbot (Barbot)	✓	✓	<i>Barbot (2019)</i>
EQsimu	FEM	dliu (D. Liu, Duan)	✓	✓	<i>Liu et al. (2020)</i>
GARNET	FDM	li (M. Li, Dal Zilio, Pranger, van Dinther)	✓	✓	<i>Pranger (2020)</i>

[†] The names of simulations displayed on our online platform

Table 3. Model parameters in BP4-QD simulations

Code Name	Simulation	Grid Spacing ^a	Domain Size ^b	BC ^c
BICycle	jiang	1, 0.5	(192, 96, ∞)	P
	lambert	1, 0.5	(180, 90, ∞)	P
Motorcycle	barbot	1, 0.5	(120, 80, ∞)	P
HBI	ozawa	1, 0.5	(120, 80, ∞)	D
Unicycle	barbot	1, 0.5	(120, 80, ∞)	D
EQsimu	dliu	1	(120, 120, 200)	D
GARNET	li	1	(120, 100, 120)	D

^a The grid spacings (in km) in simulations submitted by each modeling group.

^b The total dimensions (in km) of the model domain in the format of (L_2, L_3, L_1) .

^c Displacement (D) or periodic (P) boundary conditions (BC) in the x_2/x_3 directions.

Table 4. Model parameters in BP5-QD simulations

Code Name	Simulation	Grid Spacing ^a	Domain Size ^a	BC ^a
BICycle	jiang	2, 1, 0.5	(192, 96, ∞)	P
	lambert	2, 1, 0.5, 0.25	(180, 90, ∞)	P
ESAM	liu	2, 1, 0.5, 0.25	(128, 40, ∞)	P/D ^b
FDRA	cattania	1, 0.5	(10 ⁴ , 10 ⁴ , ∞)	D
HBI	ozawa	1, 0.5	(100, 40, ∞)	D
TriBIE	dli	2, 1, 0.5	(140, 60, ∞)	D
Unicycle	barbot	2, 1, 0.5	(100, 40, ∞)	D
EQsimu	dliu	2, 1, 0.5	(120, 60, 100)	D
GARNET	li	2, 1	(120, 60, 60)	D

^a Same parameters shown in Table 3.

^b Periodic and displacement BCs in the along-strike and along-dip directions, respectively.

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