

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 major computational and physical factors

Corresponding author: Junle Jiang, jiang@ou.edu

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 find excellent quantitative agreement among simulated outputs for sufficiently large model domains and small 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

Earthquakes and fault zone processes occur over time scales ranging from milliseconds to millennia and longer. Computational models are increasingly 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 find 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 for earthquakes. Understanding the sensitivity of simulation

69 outputs will help test models against real-world observations. Our community efforts can serve as a
70 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., [Andrews, 1976a,b](#); [Ben-Zion, 2001](#); [Bhat et al., 2007](#); [Bizzarri and Cocco, 2003, 2006](#); [Day,](#)
81 [1982](#); [Das and Aki, 1977](#); [Duan and Day, 2008](#); [Dunham et al., 2011a,b](#); [Gabriel et al., 2012](#);
82 [Harris et al., 1991, 2021](#); [Kozdon and Dunham, 2013](#); [Lozos et al., 2011](#); [Ma and Beroza, 2008](#);
83 [Madariaga et al., 1998](#); [Mikumo and Miyatake, 1978, 1993](#); [Nielsen et al., 2000](#); [Olsen et al., 1997](#);
84 [Ripperger et al., 2007](#); [Shi and Day, 2013](#); [Tinti et al., 2021](#); [Wollherr et al., 2019](#); [Xu et al., 2015](#)).
85 These simulations are limited to single-event scenarios and subject to imposed artificial prestress
86 conditions and ad hoc nucleation procedures. For larger-scale fault network systems, *earthquake*
87 *simulators* aim to produce complex spatiotemporal characteristics of seismicity over millennial
88 time scales ([Richards-Dinger and Dieterich, 2012](#); [Robinson and Benites, 1995, 1996, 2001](#); [Shaw](#)
89 [et al., 2018](#); [Tullis et al., 2012](#)). The formidable computational demand inevitably requires simplification
90 and approximation of some key physical features that could influence or dominate earthquake and
91 fault interactions, such as seismic waves, slow slip, tectonic loading, and inelastic response.

92 To understand earthquake system dynamics, it has been widely recognized that we need models
93 that simulate fault behavior over multiple seismic events and the intervening periods of aseismic
94 deformation. To address this need, numerical simulations of Sequences of Earthquakes and Aseismic
95 Slip (SEAS) are developed to consider all phases of earthquake faulting, from slow loading to
96 earthquake nucleation, propagation and termination over time scales of milliseconds to millennia
97 in a unified, self-consistent framework (Figure 1; [Ben-Zion and Rice, 1995](#); [Lapusta et al., 2000](#);
98 [Rice, 1993](#)). While retaining computational rigor, SEAS models incorporate the structure, rock
99 properties, friction, and rheology of a fault zone, and produce the pre-, inter-, and post-seismic slip
100 and the resulting stress redistribution that ultimately lead to spontaneous earthquake nucleation
101 and dynamic ruptures. SEAS models can include many physical processes relevant to long-term
102 slip, such as evolving shear resistance of the fault zone affected by shear heating, fluid effects, and
103 interseismic healing, wave-mediated inertial effects during dynamic rupture, folding, viscoelasticity,

104 and fluid flow (e.g., *Allison and Dunham, 2018; Barbot, 2018; Lambert and Barbot, 2016; Noda*
105 *and Lapusta, 2010; Sathiakumar et al., 2020; Thomas et al., 2014; Zhu et al., 2020*). This modeling
106 framework can help determine and quantify which physical factors control diverse observables such
107 as ground deformation and shaking, and the frequency, size, and rupture style of microseismicity
108 and large earthquakes. SEAS models also bridge the domains of dynamic rupture simulations and
109 earthquake simulators, providing physically justified approximations and self-consistent choices for
110 initial conditions and earthquake nucleation procedures.

111 Developments in SEAS models over the past two decades have led to increased diversity and
112 complexity of models and closer connections between simulations and observations from the lab
113 and field. For example, numerical models have been combined with seismic and geodetic observations
114 to study fault frictional properties (e.g., *Barbot et al., 2009; Dublanche et al., 2013; Floyd et al.,*
115 *2016; Hori et al., 2004; Jiang and Fialko, 2016; Johnson et al., 2006; Mitsui and Iio, 2011; Tymofyeyeva*
116 *et al., 2019*), tremor and slow slip (e.g., *Dal Zilio et al., 2020; Dublanche, 2018; Hawthorne and*
117 *Rubin, 2013; Luo and Ampuero, 2018; Mele Veedu and Barbot, 2016; Shibazaki and Iio, 2003;*
118 *Wang and Barbot, 2020*), foreshock and aftershock sequences (e.g., *Cattania and Segall, 2021;*
119 *Kaneko and Lapusta, 2008; Perfettini and Avouac, 2007; Noda et al., 2013*), and characteristics
120 of small and large earthquake ruptures (e.g., *Barbot et al., 2012; Cattania and Segall, 2019; Chen*
121 *and Lapusta, 2009; Jiang and Lapusta, 2016, 2017; Lambert and Lapusta, 2021*). The framework
122 of earthquake sequence modeling is also adopted in diverse settings, which include subduction
123 zones (e.g., *Hori et al., 2004; Liu and Rice, 2005, 2007; Li and Liu, 2016, 2017; Shi et al., 2020;*
124 *Van Dinther et al., 2013*), collision zones (e.g., *Dal Zilio et al., 2018; Michel et al., 2017; Qiu et al.,*
125 *2016*), and induced seismicity phenomena (e.g., *Dieterich et al., 2015; Kroll and Cochran, 2021;*
126 *McClure and Horne, 2011*), among many applications.

127 While researchers continue to build more advanced and detailed SEAS models, verification
128 of different numerical codes is essential to ensure credible and reproducible results, and sustain
129 scientific progress. In practice, analytical solutions are generally not available, even for simple
130 SEAS problems, and convergence of simulations to a high-resolution reference case may not always
131 detect systematic issues in complex numerical codes. An alternative means for verifying model
132 results are comparisons of independent numerical codes from different research groups. As an
133 example, the SCEC/USGS Spontaneous Rupture Code Verification Project pioneered the code
134 comparison exercise and improved confidence in the outcomes of dynamic rupture simulations
135 (*Barall and Harris, 2015; Day et al., 2005; Harris et al., 2009, 2018*).

136 Verification of SEAS models is confronted with distinct challenges, due to the wide range
137 of spatial and temporal scales that characterize the earthquake source behavior and the diversity
138 of numerical algorithms and codes. For example, codes based on the spectral boundary element
139 method (SBEM) (*Barbot, 2021; Lapusta and Rice, 2003; Lapusta and Liu, 2009*) are highly efficient

140 in solving for fully dynamic earthquake ruptures, albeit with relatively simple fault geometry and
141 bulk. Codes based on the boundary element method (BEM) (e.g., [Barbot, 2019](#); [Kato, 2016](#); [Liu,](#)
142 [2013](#); [Luo et al., 2017](#); [Nakata et al., 2012](#); [Rice and Tse, 1986](#); [Segall and Bradley, 2012](#); [Tse](#)
143 [and Rice, 1986](#)) can efficiently simulate earthquake ruptures in problems with more complex fault
144 geometry, often with the approximation of inertia (i.e., *quasi-dynamic* earthquakes). Codes based
145 on the finite difference method (FDM) (e.g., [Allison and Dunham, 2018](#); [Erickson and Dunham,](#)
146 [2014](#); [Erickson et al., 2017](#); [Herrendörfer et al., 2018](#); [Mckay et al., 2019](#); [Pranger, 2020](#)), finite
147 element method (FEM) (e.g., [Liu et al., 2020](#); [Luo et al., 2020](#); [Tal and Hager, 2018](#)), and spectral
148 element method (SEM) (e.g., [Kaneko et al., 2011](#); [Thakur et al., 2020](#)) can flexibly incorporate
149 geometrical and structural complexity in earthquake simulations, usually at a greater computational
150 cost than BEM. For all these codes, common challenges lie in the interaction between the highly
151 nonlinear nature of the SEAS problems and numerical round-off errors, which can lead to the divergence
152 of model behaviors with increasing simulated time ([Lambert and Lapusta, 2021](#)). Simulation techniques
153 are further complicated when additional physical factors, e.g., fault roughness, material heterogeneities,
154 and bulk inelastic responses, are incorporated or approximated (e.g., [Abdelmeguid et al., 2019](#);
155 [Dal Zilio et al., 2022](#); [Romanet and Ozawa, 2021](#)). However, considering such complexity may
156 be crucial in our efforts to understand earthquakes and predict seismic hazards.

157 This study represents ongoing community efforts in the SEAS working group, supported by
158 the Southern California Earthquake Center (SCEC) to perform code verification exercises for SEAS
159 models. We reported the community initiative and results from our first two benchmarks, BP1-QD
160 and BP2-QD, for two-dimensional (2D) SEAS problems in [Erickson et al. \(2020\)](#). We gather 11
161 independent modeling groups using different numerical codes to participate and compare 2D SEAS
162 simulations. Through code comparisons, we identify how various computational factors, such
163 as the numerical resolution, domain size, and boundary conditions, influence simulation results
164 in 2D antiplane problems. Our exercises demonstrated excellent agreement in simulations with
165 a sufficiently small grid spacing and large domain size, lending confidence to the participating
166 numerical codes. We also found that artificial complexity in earthquake patterns can arise due
167 to insufficient numerical resolution for key physical length scales, although ensemble-averaged
168 measures, such as earthquake recurrence times, are more robust than observables from individual
169 simulations, even at poor numerical resolutions.

170 As our community and code capabilities grow, we have made substantial progress in benchmark
171 efforts for three-dimensional (3D) SEAS problems. Here, we present our recent development of
172 two new 3D benchmarks, BP4 and BP5. The dramatically increased computational demand for 3D
173 problems requires us to balance the simplicity and realism of the benchmark problems (Section 2).
174 Although we present the complete benchmark descriptions that include both fully dynamic (FD;
175 including inertia) and quasi-dynamic (QD; approximating inertia) formulations of earthquake ruptures,

176 our code comparison results are limited to the quasi-dynamic problems. We examine choices of
177 numerical implementations among the modeling groups to ensure consistent comparisons of a large
178 set of 3D simulations (Section 3). We also design new strategies and metrics for code verification
179 for complex 3D simulations that are often done at the upper limit of numerical resolutions (Section 4).
180 In particular, we explore the sensitivity of diverse model outputs and observables to major computational
181 and physical factors. Through these efforts, we aim to improve and promote a new generation of
182 rigorous, robust numerical codes for SEAS problems, and to inform and interact with other communities
183 that are tackling similar computational challenges in nonlinear, multiscale, multi-physics problems
184 (e.g. [Buiter et al., 2016](#); [Matsui et al., 2016](#); [Maxwell et al., 2014](#); [Nearing et al., 2018](#)).

185 2 Community Benchmark Development

186 2.1 Strategy for Benchmark Design

187 We follow the principle of starting simple and incrementally adding complexity in the design
188 process of SEAS benchmarks. For 2D benchmark problems (BP1-QD and BP2-QD), a 1D fault in
189 a 2D antiplane setting was considered to explore how the computational domain size and boundary
190 conditions affect simulation results and how numerical resolution (grid spacing or cell size) influences
191 earthquake patterns and statistics ([Erickson et al., 2020](#)). Overall, we aim to verify different numerical
192 codes through a detailed comparison of simulated fault behavior over multiple time scales. These
193 efforts require a better understanding of the dependence of fault slip history on fault properties,
194 friction laws, initial conditions, model spin-up, and other factors.

195 Our findings and experience from 2D benchmark exercises prepare us for more complicated
196 3D benchmark problems. We need to design 3D benchmarks that are tractable for the widest suite
197 of numerical codes and thereby maximize participation of modelers, especially considering the
198 higher computational cost of 3D simulations and distinct capabilities of different codes in the community.
199 For example, codes based on the spectral boundary element method, e.g., BICycle ([Lapusta and
200 Liu, 2009](#)), are efficient in solving for quasi-dynamic or fully dynamic earthquake ruptures, but
201 rely on periodic boundary conditions and free surface approximations. Methods based on the finite
202 element method, e.g., EQsimu ([Liu et al., 2020](#)), can incorporate more complicated fault geometries
203 and bulk, including a rigorous treatment of the free surface, but need to balance the domain size
204 with a reasonable computational cost.

205 While we can in principle compare the full spectrum of fault behavior in SEAS models, the
206 focus of our exercise here is on reproducing earthquake nucleation, rupture, and recurrence. With
207 the computational cost in mind, we design benchmark problems where a direct comparison of
208 individual earthquakes is feasible (hence a consistent nucleation location is desirable). We then
209 assess the agreement of important model observables and their sensitivity to computational and

210 physical factors. A better understanding of the roles of various inputs and outputs in SEAS models
 211 will guide us in developing more complicated benchmarks and validating SEAS models in future.

212 Since the participation of many modelers is essential to the success of the code verification
 213 exercise, we seek to build a consensus in the community at the outset of our benchmark design
 214 process. We conducted surveys among the interested modelers to decide on the most preferred
 215 benchmark problems. For instance, we have chosen to focus on quasi-dynamic problems for our
 216 initial 3D benchmarks, BP4 and BP5, given that many numerical codes cannot yet incorporate
 217 full inertial effects but adopt the radiation damping approximation (*Rice, 1993*). While we assess a
 218 myriad of simulation outputs and develop metrics for model comparisons, we are flexible about the
 219 submitted simulation data, given that sometimes substantial code development is needed. During
 220 the subsequent development following initial comparisons of benchmark BP4, we learned lessons
 221 about the computational cost and have accordingly revised the model parameters and output types
 222 for benchmark BP5, hence some minor differences exist between the two benchmarks.

223 2.2 Benchmark Problem Setup

224 We have developed two benchmarks, BP4 and BP5, for 3D SEAS simulations (Figure 2). Our
 225 first 3D benchmark problem, BP4, considers a 3D homogeneous, isotropic, linear elastic whole
 226 space 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
 227 the fault-normal, along-strike, and along-dip directions, respectively. A vertical strike-slip fault
 228 is embedded at $x_1 = 0$. We use the notation “+” and “-” to refer to the side of the fault with x_1
 229 positive and negative, respectively. We assume 3D motion, denoting components of the displacement
 230 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,
 231 involves a fault with half the vertical dimension in a 3D half-space, defined by $\mathbf{x} = (x_1, x_2, x_3) \in (-\infty, \infty) \times (-\infty, \infty) \times (0, \infty)$,
 232 with a free surface at $x_3 = 0$ and x_3 as positive downward. Several model parameters in BP5 are
 233 adjusted to allow for reduced computational demand compared with BP4.

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

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

$$245 \quad \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \boldsymbol{\sigma} \quad \text{for FD problems;} \quad (1a)$$

$$246 \quad 0 = \nabla \cdot \boldsymbol{\sigma} \quad \text{for QD problems,} \quad (1b)$$

248 where \mathbf{u} is the displacement vector, $\boldsymbol{\sigma}$ is the stress tensor, and ρ is the material density. Hooke's
 249 law relates the stress tensor $\boldsymbol{\sigma}$ to strain tensor $\boldsymbol{\epsilon}$ by

$$250 \quad \sigma_{ij} = K \epsilon_{kk} \delta_{ij} + 2\mu \left(\epsilon_{ij} - \frac{1}{3} \epsilon_{kk} \delta_{ij} \right), \quad i, j = 1, 2, 3, \quad (2)$$

251 where K and μ are the bulk and shear moduli, respectively, and the use of subscript k follows the
 252 Einstein summation convention. The strain-displacement relations are given by

$$253 \quad \epsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad i, j = 1, 2, 3. \quad (3)$$

254 **2.2.1 Boundary and Interface Conditions**

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

$$257 \quad \sigma_{j3}(x_1, x_2, 0, t) = 0, \quad j = 1, 2, 3. \quad (4)$$

258 Since the fault is always under compression in these benchmarks, there is no opening on the fault,
 259 namely:

$$260 \quad u_1(0^+, x_2, x_3, t) = u_1(0^-, x_2, x_3, t). \quad (5)$$

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

$$262 \quad s_j(x_2, x_3, t) = u_j(0^+, x_2, x_3, t) - u_j(0^-, x_2, x_3, t), \quad j = 2, 3, \quad (6)$$

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

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

$$267 \quad \sigma_{j1}(0^+, x_2, x_3, t) = \sigma_{j1}(0^-, x_2, x_3, t), \quad j = 1, 2, 3, \quad (7)$$

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

273 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
 274 dot notation indicates the time derivative, and denote slip rate amplitude as the norm of the slip rate
 275 vector, $V = \|\mathbf{V}\|$. The shear stress vector is given by $\boldsymbol{\tau} = (\tau_y, \tau_z)$.

276 In both benchmark problems, we assign a frictional domain on the fault, Ω_f , with dimensions
 277 of (L_f, W_f) in the along-strike and along-dip directions, where fault slip is governed by a rate- and
 278 state-dependent friction law (Dieterich, 1979; Ruina, 1983; Marone, 1998). The shear stress on the
 279 frictional fault $\boldsymbol{\tau}$ is set to always equal the frictional strength $\mathbf{F} = (F_2, F_3)$, namely

$$280 \quad \boldsymbol{\tau} = \mathbf{F}(\bar{\sigma}_n, \mathbf{V}, \theta), \quad (8)$$

281 where the effective normal stress is $\bar{\sigma}_n = \sigma_n - p$, with normal stress σ_n and pore pressure p , and θ
 282 is a state variable.

283 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
 284 prestress $\boldsymbol{\tau}^0$, the shear stress change due to quasi-static deformation $\Delta\boldsymbol{\tau}$, and the radiation damping
 285 approximation of inertia $\eta\mathbf{V}$ (Rice, 1993), where $\eta = \mu/2c_s$ is half the shear-wave impedance for
 286 shear wave speed $c_s = \sqrt{\mu/\rho}$, with the shear modulus μ and density ρ . For fully dynamic problems,
 287 $\boldsymbol{\tau} = \boldsymbol{\tau}^0 + \Delta\boldsymbol{\tau}$, where $\Delta\boldsymbol{\tau}$ includes all elastodynamic stress transfers due to prior slip on the fault.

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

$$290 \quad \mathbf{F}(\bar{\sigma}_n, \mathbf{V}, \theta) = \bar{\sigma}_n f(V, \theta) \mathbf{V}/V. \quad (9)$$

291 The effective normal stress is taken to be uniform in space and unvarying in time, which is valid
 292 due to the symmetry across the planar fault and no fault opening. Since only the effective normal
 293 stress, not the normal stress, matters in Eq. 9, we use σ_n as a simpler notation for the effective
 294 normal stress in the remainder of this paper. We adopt a regularized formulation for the rate-and-state
 295 friction coefficient (Lapusta et al., 2000)

$$296 \quad f(V, \theta) = a \cdot \operatorname{arcsinh} \left[\frac{V}{2V^*} \exp \left(\frac{f^* + b \ln(V^*\theta/D_{RS})}{a} \right) \right], \quad (10)$$

297 where D_{RS} is the characteristic state evolution distance, f^* is the reference friction coefficient
 298 determined at the reference slip rate V^* , and a and b are the parameters for the direct and evolution
 299 effects, respectively. We couple Eq. 10 with the aging law for the evolution of the state variable
 300 (Dieterich, 1979; Ruina, 1983):

$$301 \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{D_{RS}}, \quad (11)$$

302 The spatial distributions of parameters a and b are chosen to create a seismogenic zone with velocity-weakening
 303 (VW; $a - b < 0$) frictional properties that is surrounded by regions with velocity-strengthening
 304 (VS; $a - b > 0$) frictional properties, with a linear transition zone in-between. We use the same

305 value for parameter b throughout the rate-and-state fault (denoted as b_0) and different values for
 306 parameter a in the VW and VS regions (denoted as a_0 and a_{\max} , respectively).

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

$$309 \quad V_2(x_2, x_3, t) = V_L, \quad (12a)$$

$$310 \quad V_3(x_2, x_3, t) = 0, \quad (12b)$$

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

$$313 \quad u_2^\pm = \pm \frac{V_L t}{2}, \quad (13a)$$

$$314 \quad u_1 = u_3 = 0, \quad (13b)$$

316 where the superscript “ \pm ” refers to the “+/-” sides of the fault, associated with positive and negative
 317 displacement values, respectively. By imposing this boundary condition, we consider displacements
 318 \mathbf{u} that are only caused by slip, excluding the deformation that produced the prestress τ^0 in the absence
 319 of fault slip. As a result, σ are essentially stress changes associated with the displacement field
 320 \mathbf{u} relative to the prestress state. For the fully dynamic problem, Eq. 13 must be augmented with
 321 radiation conditions that permit outgoing seismic waves (e.g., [Bonnet, 1999](#)). We describe an infinitely
 322 large domain in our benchmarks and leave choices of numerical implementation and approximation
 323 to modelers (see Section 3.1).

324 **2.2.2 Initial Conditions**

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

$$327 \quad \mathbf{V} = (V_{\text{init}}, V_{\text{tiny}}), \quad (14)$$

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

$$331 \quad \theta(x_2, x_3, 0) = D_{\text{RS}}/V_{\text{init}}. \quad (15)$$

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

$$334 \quad \tau^0 = a\sigma_n \cdot \operatorname{arcsinh} \left[\frac{V_{\text{init}}}{2V^*} \exp \left(\frac{f^* + b \ln(V^*/V_{\text{init}})}{a} \right) \right] + \eta V_{\text{init}}. \quad (16)$$

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

$$338 \quad s_j(x_2, x_3, 0) = 0, \quad j = 2, 3. \quad (17)$$

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

342 To break the lateral symmetry of the fault and facilitate code comparisons, we add a square
 343 zone within the VW region, with a width of $w = 12$ km and a center at $(-22.5$ km, -7.5 km) in BP4
 344 and $(-24$ km, -10 km) in BP5, as a prescribed nucleation location for the first simulated earthquake.
 345 To do that, we impose a higher initial slip rate, V_i , in the x_2 direction within this square zone at
 346 $t = 0$, while keeping the initial state variable $\theta(x_2, x_3, 0)$ unchanged. The resultant higher pre-stress
 347 is calculated by replacing V_{init} with V_i in Eq. 16. This initial condition leads to an immediate initiation
 348 of the first event. In BP5, we additionally use a smaller characteristic state evolution distance D_{RS}
 349 in this prescribed nucleation zone to promote the nucleation of subsequent earthquakes in the same
 350 areas (see the next section). We note that future benchmarks can use a spatially smoother function
 351 of the physical properties within the nucleation zone to minimize the influence of spatial discretizations
 352 in numerical models (*Galis et al., 2015*).

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

359 2.2.3 Critical Physical Length Scales

360 Numerical resolution is a critical issue for 3D benchmark problems, as we need to balance the
 361 computational cost and adequate resolution to achieve acceptable model agreement. Two physical
 362 length scales are generally important to consider in these problems. The first length scale, often
 363 referred to as the process zone or cohesive zone, Λ , describes the spatial region near the rupture
 364 front under which breakdown of fault resistance occurs, and shrinks as ruptures propagate faster
 365 (*Freund, 1990; Palmer and Rice, 1973*). For faults governed by the rate-and-state friction, the quasi-static
 366 process zone at a rupture speed of 0^+ , Λ_0 , can be estimated as follows (*Day et al., 2005; Lapusta*
 367 *and Liu, 2009*):

$$368 \Lambda_0 = C \frac{\mu D_{\text{RS}}}{b \sigma_n}, \quad (18)$$

369 where C is a constant of order 1.

370 The second length scale that controls model behavior is the nucleation size h^* , which determines
 371 the minimum size of the velocity-weakening region over which spontaneous nucleation may occur
 372 (*Ampuero and Rubin, 2008; Rice and Ruina, 1983; Rubin and Ampuero, 2005*). For 3D problems,

373 the nucleation size can be estimated for the aging law for $0.5 < a/b < 1$ as follows (*Chen and*
 374 *Lapusta, 2009*):

$$375 \quad h^* = \frac{\pi}{2} \frac{\mu b D_{RS}}{(b-a)^2 \sigma_n}. \quad (19)$$

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

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

390 2.3 Model Outputs

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

397 For local time series data, we are interested in resolving the time evolution of fault slip rates,
 398 shear stress, and off-fault displacements throughout the coseismic, postseismic, and interseismic
 399 periods. The global source properties refer to the evolving maximum slip rates and moment rates
 400 over the entire seismogenic fault areas, which are useful for determining the precise time of initiation
 401 and cessation of individual earthquakes. The catalog data contain key characteristics of simulated
 402 earthquakes, including their initiation and termination times, coseismic slip, and static stress drop.
 403 The beginning and end of the coseismic period are determined as the times at which any point
 404 on the fault reaches above or all points drop below a threshold slip rate, V_{th} (chosen as 0.03 m/s),
 405 respectively. We then estimate coseismic slip and stress drop as the change in the amplitude of fault
 406 slip and shear stress (negative stress change corresponds to positive stress drop).

407 The slip and stress profiles in the along-strike and along-dip directions illustrate the general
408 patterns of earthquake sequences and the partitioning of seismic and aseismic slip. The rupture
409 time data record the time when each point on the fault reaches a certain threshold slip rate ($V_{th} =$
410 0.03 m/s) during the first earthquake. Note that the relative rupture times are independent of V_{th}
411 and we can use maximum slip rates and rupture time data to construct contours of rupture fronts
412 associated with different values of V_{th} .

413 2.4 Modeling Groups

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

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

427 More modeling groups participated in BP5-QD than BP4-QD, due to considerations of timing
428 and/or computational costs (Table 2). Given the similar problem setup of the two benchmarks, we
429 present main results for BP4-QD and more complete comparisons for BP5-QD, using a selected
430 suite of simulations listed in Tables 3 and 4. Several modelers have performed independent simulations
431 using the same code (BICycle and GARNET). These efforts ensure correct model setup and code
432 execution and, in the case of BICycle, expand the set of simulations and reveal the important effect
433 of time stepping parameters (see Section 3.3). Due to limitations in code development and computational
434 resources or different numerical methods, not all modeling groups have submitted all forms of
435 requested simulation outputs. Our comparisons use the entire set of available simulation results.

436 3 Computational Factors

437 Both 3D SEAS benchmarks are computationally challenging: BP4-QD requires better numerical
438 resolution and BP5-QD incorporates additional effects associated with the free surface. The overall
439 high computational cost means that we have to carefully consider the effects of computational

440 domain truncation and grid discretization on simulations that are performed near the marginal
441 numerical resolutions. We elaborate on these computational factors in this section to provide important
442 context to our code comparison results. We also comment on the time stepping schemes, an important
443 ingredient in SEAS simulations.

444 3.1 Domain Truncation and Boundary Conditions

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

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

465 BEM/SBEM simulations with ESAM, BICycle, and Motorcycle adopt periodic boundaries
466 that effectively involve infinite replicas of the model domain in the along-strike direction; large
467 areas with the imposed loading rate were included to minimize the effect of adjacent fault replicas
468 on simulated fault behavior. Simulations with BICycle also have periodic boundary conditions
469 in the along-dip direction and, in the half-space problem BP5, approximate the free surface by
470 adding a mirror image of the physical domain. Nonetheless, in our comparisons we do not observe
471 systematic differences between BICycle and other simulations, which suggests that the effect of
472 these approximations is comparable to or smaller than other sources of discrepancies between
473 different simulation methods.

474 For volume-discretized methods such as EQsimu and GARNET, modelers need to truncate
475 model domains in all three dimensions. For the far-field boundaries in the fault-normal direction,
476 EQsimu and GARNET simulations use a Dirichlet boundary conditions for displacements via
477 a fixed slip rate. When truncated fault-normal dimensions are not sufficiently large, the results
478 are quantitatively influenced by this boundary condition. In BP5-QD, EQsimu modelers choose
479 the steady interseismic velocity predicted by $V_2(x_1) = V_L/\pi \cdot \arctan(x_1/D)$ (*Savage and Burford,*
480 [1973](#)), specifically, $V_2 \approx 4 \times 10^{-10}$ m/s (with $D = 18$ km and $x_1 = L_1/2 = 50$ km), to impose displacement
481 boundary conditions in the far field. Both EQsimu and GARNET impose stress-free conditions at
482 the remaining boundaries of the truncated domain, which includes two planes perpendicular to the
483 fault and the bottom layer.

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

488 3.2 Grid Discretization

489 The two benchmarks, especially BP5-QD, have a relatively large grid spacing by design, which
490 is a nontrivial factor when we compare different simulations. For example, different codes represent
491 local fault properties within piece-wise constant (BEM) or piece-wise linear (FEM) elements, or
492 on Fourier sample points (SBEM). Most BEM codes use rectangular elements, whereas TriBIE
493 uses triangular elements with their centroids on irregular grids. Additionally, FDM code GARNET
494 uses a fully staggered grid, which means that velocities are not located on the same grid points with
495 some other properties. Consequently, the computational grid points in these simulations are often
496 offset from the observational points specified in the benchmark description. Even though these
497 numerical codes are designed to solve the same continuum problem, different discrete representations
498 of local physical properties, when combined with a relatively large grid spacing, result in nontrivial
499 truncation errors that are different among these codes.

500 During early code comparisons for BP5-QD, we noticed that a spatial offset in the computational
501 grid can lead to noticeable differences in the location and size of the prescribed nucleation region
502 and rupture front development during the first event. Even though we have improved the consistency
503 in model setups through several iterations among modelers, the inherent differences in computational
504 methods continue to contribute to the discrepancies in the simulated outcomes. While this issue
505 does not substantially affect our 2D benchmark problems (*Erickson et al., 2020*), it appears important
506 in the comparisons for our 3D benchmarks, likely due to the use of larger cells.

3.3 Time Stepping Schemes

The scheme of non-uniform, adaptive time stepping is essential in SEAS simulations that resolve various phases of earthquake source processes. We do not cover this computational aspect in the benchmark description and presume that modelers will adopt the optimal time stepping schemes for their numerical codes. Most codes use adaptive Runge-Kutta methods for time stepping. FDM code GARNET uses a linear multistep method (BDF2, second order backward differentiation formula) for their time stepping ([Pranger, 2020](#)). SBEM code BICycle determines the adaptive time steps based on maximum slip rates and stability conditions derived from constitutive laws ([Lapusta et al., 2000](#)), which is also adopted in other codes, such as EQsimu and GARNET.

In practice, suboptimal time stepping can complicate model comparisons. In earlier comparisons for BP4-QD, one BICycle simulation ([jiang](#), denoted as BICycle-1 hereinafter) exhibited frequent aseismic transients prior to large events, while these features were absent in another BICycle simulation ([Lambert](#), denoted as BICycle-2 hereinafter). We later tracked down the cause of this discrepancy: the latter simulation adopts a smaller constant factor in estimating the time step size (Eq. 18 in [Lapusta et al. \(2000\)](#)) and the use of finer time steps eliminates the aseismic transients, which are apparently numerical artifacts. We encountered a similar situation with EQsimu simulations, where a simple refinement of all time steps removed numerical transients and improved model agreement. Since we have corrected this issue in updated models, the choice on time stepping approaches should have a minimal influence on the comparison results presented below.

4 Comparisons of 3D Simulations

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

537 **4.1 Whole-Space Problem BP4-QD**

538 **4.1.1 Initial Rupture Propagation**

539 The initial stage of the simulations provides a few crucial observables that are minimally affected
 540 by cumulating numerical errors. For benchmark BP4-QD, we first compare the coseismic rupture
 541 fronts during the first event in simulations with the suggested grid spacing ($\Delta x = 500$ m) (Figure 4a).
 542 We adopt a higher threshold slip rate than specified in the benchmarks, $V_{th} = 0.1$ m/s, to define
 543 the initiation time of the earthquake as the moment when any point on the fault reaches V_{th} ; we
 544 later explore how a different V_{th} affects BP5-QD comparisons in Section 4.2.1. In Figure 4a, we
 545 find a discrepancy of <1 s in local rupture arrival time (i.e., $<3\%$ in average rupture speed) among
 546 simulations. We consider such a match of rupture fronts satisfying, given that the rupture arrival
 547 time has been shown to be a sensitive indicator of numerical precision in dynamic rupture simulations
 548 [Day et al. \(2005\)](#). The first simulated earthquake initiates within the prescribed nucleation zone
 549 and propagates outward through the rest of the VW region over a period of ~ 30 s. The suite of
 550 simulations with a grid spacing of 1000 m includes two volume-discretized codes. While the discrepancy
 551 in rupture times increases to a few seconds among all codes, the qualitative rupture pattern is unchanged
 552 in the coarser-resolution simulations.

553 **4.1.2 Long-term Fault Behavior**

554 We then assess the long-term fault behavior, in terms of maximum slip rates over the seismogenic
 555 fault areas, in simulations with different resolutions (Figure 5). The simulations with a 1000 m
 556 grid spacing come from a wider range of codes and show similar features of earthquake recurrence
 557 and interseismic periods, with fault slip rates varying between $\sim 10^{-9}$ and 1 m/s. Since the spatial
 558 model resolution is suboptimal, the simulations show a large variability in the transient aseismic
 559 slip between large earthquakes. These transient features are completely absent in simulations with a
 560 500 m grid spacing and hence are numerical artifacts, rather than physical features. We also notice
 561 a persistent discrepancy of large event recurrence intervals which grows with the simulated time,
 562 even among better resolved simulations.

563 The computational demand of 3D benchmark problems prohibits a comprehensive self-convergence
 564 test of all participating numerical codes. We use the SBEM simulations (BICyclE-2) to demonstrate
 565 that self-convergence of simulation results may not show the true solution of the mathematically
 566 defined benchmark problems, when the domain size is not sufficiently large. In Figure 6, we show
 567 simulations with a range of grid spacings (125, 250, 500, and 1000 m) and three computational
 568 domain sizes: (120 km, 90 km), (240 km, 180 km), and (480 km, 360 km) for the along-strike and
 569 along-dip model dimensions, denoted as S1, S2, and S3, respectively.

570 The comparison of these simulations using the same code suggests challenges in assessing
571 model agreement in 3D problems. First, with a smaller computational domain size (S1), simulations
572 appear to converge to a similar pattern of long-term behavior (Figure 6a–b). However, when the
573 computational domain size is increased (S2 and S3), the simulations produce different earthquake
574 patterns, with alternating nucleation locations (Figure 6c–d). This difference results in a minor,
575 though noticeable, change in the recurrence time of subsequent events (Figure 6a). The sensitivity
576 of nucleation location in BP4-QD likely stems from the spatially uniform frictional properties and
577 near-symmetric stress field associated with the fault-spanning quasi-dynamic earthquake ruptures.
578 Even though we are approaching the computational limit, we expect that model behavior will presumably
579 stabilize and converge to the same pattern as domain size substantially increases, as we have seen in
580 2D problems (*Erickson et al., 2020*).

581 We note that, physically, these results arise since the two ends of the fault represent similar
582 favorable nucleation locations in the uniform fault model setup, which allows minor computational
583 changes to affect which nucleation location wins. This further implies that, on such a fault, minor
584 outside perturbations (not modeled here), such as stress changes from slip on nearby faults, would
585 determine the nucleation location. Note also that the incorporation of full wave-mediated inertial
586 effects, not considered in this benchmark, are expected to create much larger differences in the
587 model response based on prior studies (*Lapusta and Liu, 2009; Thomas et al., 2014*).

588 **4.2 Half-Space Problem BP5-QD**

589 **4.2.1 Initial Rupture Propagation**

590 The rupture fronts of the first event in BP5-QD simulations ($V_{th} = 0.1$ m/s) show a close match
591 and slightly larger discrepancy compared with BP4-QD results, partly due to different grid spacings
592 (Figure 4). The simulated earthquake rupture propagates into the transition zones around the VW
593 region and reaches the surface, with the total rupture lasting over 30 s. The maximum discrepancy
594 in local rupture time is less than two seconds among most simulations (5–10% discrepancy in
595 rupture speeds), and a few seconds between the EQsimu simulation and others (~10% discrepancy
596 in rupture speeds) with the former showing higher rupture speeds.

597 When we use a lower threshold slip rate, $V_{th} = 0.03$ m/s, to determine the coseismic phase, the
598 rupture front contours appear more discrepant, though retaining a qualitative agreement (Figure 7a).
599 This alternative comparison reveals a large variability in the evolution of slower slip preceding the
600 earthquake rupture among simulations. We observe increased discrepancies among SBEM/BEM
601 simulations, while the largest discrepancies are associated with the two volume-discretized codes,
602 which seem to produce rupture speeds that are either higher or lower than the average values among

603 the group. Nonetheless, a smaller grid spacing helps reduce the differences in rupture fronts between
604 EQsimu and other simulations, albeit at an increased computational expense (Figure 7b).

605 **4.2.2 Long-Term Fault Behavior**

606 We first show the overall earthquake patterns in BP5-QD (Figure 8). We juxtapose the profiles
607 of fault slip evolution in the along-strike and along-dip directions from two codes, FDRA and BICycleE,
608 based on BEM and SBEM methods, respectively. The results show that, after the first earthquake,
609 later events exhibit recurrent slip patterns. The coseismic slip initiates and propagates through the
610 VW region and into the shallow VS region, whereas postseismic and interseismic slip occurs in
611 the adjacent VS regions and to a lesser extent near the surface. In contrast to BP4-QD, BP5-QD
612 simulations generally have a persistent location for earthquake initiation due to the heterogeneity in
613 frictional properties that we introduce in this benchmark.

614 We find an overall good agreement of maximum slip rates over the seismogenic fault areas
615 among simulations with the suggested resolution ($\Delta x = 1000$ m) (Figure 9a). The inter-event times
616 of simulated earthquakes vary around ~ 235 years over the 1800-year simulation period. A small
617 yet persistent difference in recurrence intervals leads to apparent divergent timing of large events in
618 simulations, especially for the EQsimu simulation which exhibits some pre-event aseismic transients.
619 Despite the minor discrepancy in rupture fronts shown earlier, the total rupture duration and static
620 stress drop of the first event match closely among simulations where catalog data are available
621 (Figure 9b–c). We determine the beginning and end of the coseismic period as the times at which
622 any point on the fault reaches above or all points drop below a threshold slip rate of 0.1 m/s, respectively,
623 to be consistent with how we estimate the rupture time in Figure 4. The simulated earthquakes have
624 robust characteristics, with rupture durations of ~ 30 s and stress drops of ~ 5 MPa.

625 We then examine the time evolution of local slip rates and shear stress on the fault, at the
626 surface ($x_3 = 0$ km) and the mid-seismogenic depth ($x_3 = 10$ km), during the first 1000 years of
627 BP5-QD simulations (Figures 10 and 11). The periodic variations in local shear stress and slip
628 rates are distinct at different depths. At the surface, the fault creeps with slip rates comparable to
629 the plate rate before dynamic rupture comes (Figure 10b, d), and hence the rapid increase of slip
630 rates to ~ 1 m/s at the rupture front results in a large direct effect on the shear stress (the vertical
631 lines in Figure 10a, c), amplified by the large value of the rate-and-state parameter there ($a = 0.04$).
632 At the same time, the smaller slip at the free surface due to its VS nature results in smaller static
633 stress drops (the difference in shear stress before and after the vertical lines that represent dynamic
634 rupture) of ~ 1 MPa.

635 In contrast, substantial static stress drops of ~ 10 MPa occur within the VW region during
636 earthquakes, followed by interseismic strain buildup, leading to slip rate variations over tens of

637 orders of magnitude (Figure 11). The direct effect during the dynamic rupture appears weaker
 638 at mid-seismogenic depth than the surface, due to the smaller value of rate-and-state parameter
 639 ($a = 0.004$). We observe a slightly larger discrepancy between simulations at depth than at the
 640 surface. Despite noticeable differences in earthquake recurrence times, all simulations accurately
 641 capture the full range of slip rate and stress variations. While simulations performed at the suggested
 642 resolution ($\Delta x = 1000$ m) already show good agreements in terms of the long-term fault behavior, a
 643 smaller grid spacing ($\Delta x = 500$ m) further improves the results.

644 **4.2.3 Coseismic Rupture and Off-Fault Behavior**

645 The comparisons of individual earthquake ruptures show consistency of different simulations,
 646 as well as complexity in the location and development of earthquake nucleation. In Figure 12,
 647 we show time evolution of slip rates and shear stresses during the first simulated event at three
 648 representative locations on the fault: within the prescribed nucleation zone ($x_2 = -24$ km, $x_3 = 10$ km),
 649 at the surface ($x_2 = x_3 = 0$ km), and within the rupture propagation zone ($x_2 = 0$ km, $x_3 = 10$ km).
 650 All time series data are aligned relative to the earthquake initiation time (defined with a threshold
 651 slip rate $V_{th} = 0.1$ m/s) in each simulation. Consistent with Figures 4b and 7, all simulations show
 652 excellent agreement of the temporal functions of slip rates and shear stresses, with minor differences
 653 in rupture arrival times and peak slip rates.

654 For the simulated fourth event, we find slightly increased model discrepancies, due to subtle
 655 differences in the earthquake nucleation condition resulting from the prior slip history (Figure 13).
 656 While most simulations retain the same source evolution function, the results from two simulations
 657 with TriBIE and EQsimu appear qualitatively different over much of the seismogenic zone. This
 658 pronounced difference is due to the different initiation locations of the earthquake, similar to the
 659 results in Figure 6. With a large nucleation zone in BP5-QD, much of the deeper VW zone hosts
 660 aseismic slip in the interseismic period. These areas can serve as alternative locations to start an
 661 earthquake, when the local stress conditions near the transition from VS to VW fault regions outcompete
 662 the processes in the prescribed nucleation zone. When we compare simulations with a halved grid
 663 spacing of 500 m, the variability of nucleation location in TriBIE and EQsimu simulations disappears.
 664 The distinct behavior of these simulations based on BEM and FEM methods suggests that the earthquake
 665 nucleation in this benchmark is still susceptible to the specific setup of a computational model.

666 To further assess model convergence, we compare the sixth event in simulations with smaller
 667 grid spacings, including most simulations at 500 m, and BICycle-2 and ESAM simulations at both
 668 500 and 250 m resolutions (Figure 14). Simulations with a grid spacing of 500 m show nearly
 669 identical source time function with small time offsets, an overall excellent agreement. However,
 670 some codes again display nucleation at the other end of the fault. Similar to the aforementioned
 671 results about TriBIE and EQsimu, we find that earthquake nucleation in finer-resolution simulations

672 (250 m) with BICycle return to the same location that matches other simulations. In spite of such
 673 variability in a few simulations, the clear improvements in model agreement suggest that different
 674 numerical codes will likely converge to the same behavior with a decreased grid spacing.

675 We also compare the off-fault behavior in simulation groups where these outputs are available
 676 (Figure 15). Note that most of these simulations explicitly solve for off-fault responses, whereas the
 677 off-fault displacements for BICycle-2 are computed from previously simulated fault slip history
 678 and analytical Green's functions (Okada, 1992). For Unicycle and TriBIE, off-fault displacements
 679 are calculated in the simulations using Okada Green's functions for only fault patches in the frictional
 680 domain, excluding deep-seated displacements. For a consistent comparison with other simulations,
 681 we add long-term displacement trend to off-fault time series from Unicycle and TriBIE simulations
 682 using $V_2(x_1) = V_L/\pi \cdot \arctan(x_1/D)$ (Savage and Burford, 1973), where we assume a locking depth
 683 D of 18 km.

684 Focusing on the first and fourth event, we observe a good qualitative agreement of surface
 685 velocity time series at various distances away from the fault, with the fourth event more challenging
 686 to match (Figure 15a–b). Overall, the discrepancies in coseismic off-fault deformation appear larger
 687 than all the on-fault properties that we have examined. This is likely due to multiple factors, including
 688 inaccurate representations of surface observation points (e.g., grid points offset from the surface)
 689 and domain truncation in the fault-normal direction. The long-term displacement histories at these
 690 off-fault locations also yield good qualitative agreements (Figure 15c).

691 **4.2.4 Model Discrepancy and Convergence**

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

704 In both simulation groups using grid spacings of 1000 and 500 m, we find that the minimum
 705 interseismic stressing rate is approximately inversely correlated with the nearly constant recurrence

706 intervals of large events (Figure 16b, d). This minimum stressing rates in volume-discretized codes
707 EQsimu and GARNET tend to deviate from the cluster of SBEM/BEM results, although the general
708 relationship between interseismic stressing rates and recurrence intervals still holds. The subsequent
709 stressing history appears more variable among many simulations, especially in cases with a grid
710 spacing of 500 m, indicating the complexity in aseismic slip evolution. These comparisons suggest
711 that stress buildup process is essentially similar across simulations and explain why these simulations
712 have more robust earthquake characteristics, even in the presence of growing discrepancies in the
713 long term.

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

724 5 Discussion

725 5.1 Important Computational and Physical Factors

726 The dominant factor controlling the response of the model is the numerical resolution (grid
727 spacing or cell size). While this is not surprising, our results show that marginal resolution significantly
728 affects the results. SEAS simulations are often done on the boundary of resolution, especially in
729 3D, due to substantial computational costs and the desire to consider realistic physical properties.
730 Our BP4-QD simulations show that the marginal cell size of 1000 m (which still resolves the quasi-static
731 process zone by 2 cells and the nucleation zone by ~ 12 cells) captures the main qualitative aspects
732 of the fault response but results in significant quantitative differences with the better-resolved simulations,
733 including much different recurrence time, larger discrepancies between different simulation approaches,
734 and artificial slow-slip transients for some codes. Reducing the cell size even to 500 m results in
735 significant improvement, with a closer match between different simulation codes.

736 For the adequate numerical resolution, we find that further differences occur due to the choice
737 of the computation domain and the associated discrepancy in the boundary and loading conditions
738 simulated. The comparisons of global fault properties in BP4-QD (Figures 5 and 6) demonstrate
739 that simulations with the same code (BICycle) produce robust earthquake patterns and properties

740 with the decrease in grid spacing. However, the apparent self-converging behaviors are associated
741 with specific domain sizes. The model discrepancy persists due to the variability of earthquake
742 nucleation locations, even when we adequately resolve the cohesive zone during rupture propagation
743 with a grid spacing of 125, 250 and 500 m. These results for BP4-QD suggest that domain truncation
744 prevents simulations from converging toward the solution to the semi-infinite domain problem, at
745 least with current computational resources.

746 Practically, this effect is relatively small in our study compared with the differences between
747 simulations with adequate and inadequate numerical resolutions. Since there is a trade-off between
748 large computational domains and fine numerical resolution, caution should be exercised when
749 modelers expand the domain size at the expense of numerical resolution. While we have explored
750 the domain effect in SBEM simulations which are relatively efficient and allow us to choose larger
751 domain sizes, similar considerations would apply to simulations using BEM/FEM/FDM methods.

752 Rupture front contours are diagnostic of rupture behavior and hence a key metric for model
753 agreement, as noted for single-event dynamic rupture simulations ([Barall and Harris, 2015](#); [Harris
754 et al., 2009](#)). In SEAS simulations, many factors can lead to large discrepancies in rupture fronts
755 even for the first event. Some issues are fixable, such as inaccurate or inconsistent model setup and
756 parameter choices (Section 3). Some factors can be mitigated in improved benchmark design. For
757 example, when revising BP5-QD, we increased the elevated initial slip rate, V_i , in the prescribed
758 nucleation zone from 0.01 m/s to 0.03 m/s. This change shortens the period of pre-rupture stress
759 buildup which turns out to be sensitive to the domain size, and improves agreement of the first
760 simulated earthquake rupture..

761 We notice inherent challenges in achieving agreements among simulations when the free
762 surface is present. The comparison between BP4-QD and BP5-QD simulations with a grid spacing
763 of 500 m (Figures 4a and 7b) suggests that the presence of the free surface and its interaction with
764 earthquake rupture contribute to increased model discrepancies, even though the cohesive zone is
765 better resolved (by more cells) in BP5-QD. Since we do not have simulations for the exact BP5-QD
766 model setup in both whole space and half-space, we cannot directly characterize the effect of the
767 free surface on 3D benchmark results.

768 Understanding the impact of heterogeneities in SEAS models is important for both benchmark
769 design and code comparison. The prestress of earthquake ruptures depends on prior fault slip history
770 and varies in space, even in the case of uniform frictional properties in BP4-QD. When designing
771 the BP5-QD problem, we introduced persistent frictional heterogeneity to promote earthquake
772 initiation at the same location, thereby largely avoiding the difficulty in comparing individual events
773 in BP4-QD. However, in some simulations, prestress heterogeneity can still outcompete the frictional
774 heterogeneity to result in different earthquake rupture patterns (Figures 13 and 14). These complexities

775 in the physical problem help reveal the subtle differences of numerical codes but also impose challenges
776 on our efforts to define and pursue successful code verification.

777 **5.2 From 2D to 3D Benchmarks**

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

784 Benchmark problems in 3D have several unique features. First, the computational constraint of
785 3D problems motivate us to design verification methods and metrics to reveal the relative sensitivities
786 of different model observables near the marginal numerical resolutions. Specifically, earthquake
787 rupture characteristics such as rupture duration, final slip, and peak slip rate appear to be more
788 robust than other longer-term observables such as recurrence intervals and nucleation phase, because
789 domain-size-dependent loading can substantially affect aseismic slip evolution. As expected, global
790 fault properties are more robust than local fault behavior. Second, the 3D nature of the problem
791 brings new physical complexity, in particular the multiple potential locations for earthquake nucleation,
792 compared with the single downdip nucleation location in 2D antiplane problem ([Erickson et al.,
793 2020](#)). The interactions of stress heterogeneity and frictional properties throughout the fault slip
794 history ultimately control earthquake nucleation, which cannot be assigned *a priori* by modelers.
795 Third, the 3D setting and the presence of a free surface enables a direct comparison of model results
796 and more complicated geophysical observations, which is important for the efforts to validate SEAS
797 models.

798 We highlight a few important outcomes of our code comparison results in connections to our
799 2D exercises. First, excellent quantitative agreements in key model observables can be achieved
800 with proper numerical resolution among different modeling group. Second, at marginal resolutions,
801 several factors combine to affect model agreements and convergence. For this reason, we find generally
802 larger discrepancies among the earthquake ruptures in 3D SEAS simulations than those in 2D
803 SEAS and 3D single-event dynamic rupture simulations. Third, even in well-resolved models,
804 long-term model observables are more sensitive than earthquake observables to minor differences
805 in computational factors.

806 **5.3 Implications for Model Validation**

807 Our successful code comparison exercises lend confidence to the accuracy of the participating
808 numerical codes, serving as an essential step towards the goal of creating valid, physics-based

809 models for earthquake source processes. In our benchmarks, many simulated physical quantities
810 can be measured or inferred using geological and geophysical observations covering disparate
811 spatial and/or temporal scales, such as seismograms, Global Navigation Satellite System (GNSS),
812 satellite imagery, and paleoseismic records, offering opportunities for model validation. Furthermore,
813 our efforts to understand how sensitive and variable model observables are to both computational
814 and physical factors also contribute to quantifying and reducing uncertainty in the data-model
815 integration. Ultimately, SEAS models validated with real-world observations could contribute to
816 estimating earthquake hazard.

817 Despite computational challenges, the SEAS modeling framework presented here rigorously
818 resolves the important spatial and temporal scales in earthquake source processes, in ways that are
819 complimentary to and synergistic with dynamic rupture simulations and earthquake simulators.
820 The computational rigor and realistic physical processes in SEAS modeling can help inform and
821 improve the choices of procedures and parameterization, and approximation of physics in other
822 modeling frameworks. Examples include the design of self-consistent pre-rupture stress conditions,
823 and assessing the role of transient slow slip in time-dependent seismic hazard.

824 **6 Conclusions**

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

832 We achieve excellent model agreements among most outputs and observables with relatively
833 large computational domain size, although discrepancies are larger than those in 3D single-event
834 dynamic rupture and 2D SEAS simulations, partly due to spatial resolutions limited by the computational
835 cost. The successful code verification exercises lend confidence to the accuracy of participating
836 numerical codes. The quantitative differences of simulation results depend on computational factors
837 such as grid discretization and spacing, model domain size, and boundary conditions. Coseismic
838 observables appear more robust than longer-term, aseismic observables that are more easily influenced
839 by long-term accumulating numerical errors and domain-size-dependent loading. An important
840 factor that can influence the interseismic behavior is the variable time stepping procedures, and
841 exploring their effect on the larger discrepancy of the aseismic observables is an important direction
842 of future work. Understanding the causes of model discrepancies and relative sensitivities of various

843 model observables are important, as researchers work towards integrating numerical simulations
844 with the increasing volumes of geological and geophysical observations.

845 The earthquake problem is a prime example of a dynamic solid Earth system that spans a wide
846 range of spatial and temporal scales. Our community-driven code verification efforts are aimed
847 at improving and promoting a new generation of rigorous, robust numerical codes for earthquake
848 science. Our results and lessons could be useful to other research areas that involve numerical
849 simulations of nonlinear, multi-scale dynamic problems.

850 **Open Research**

851 Descriptions of benchmarks BP4 and BP5 are available at [https://strike.scec.org/
852 cvws/seas/download/](https://strike.scec.org/cvws/seas/download/) (SEAS_BP4_QD.pdf and SEAS_BP5.pdf) and included as supplementary
853 materials. Our online platform (<https://strike.scec.org/cvws/seas/>) hosts the simulation
854 data for local and global fault properties and rupture times. See publications in Table 2 for the
855 availability and repositories of numerical codes. GARNET is available at [https://bitbucket.
856 org/cpranger/garnet/](https://bitbucket.org/cpranger/garnet/).

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862 exercises. J.J. analyzed all simulation results and led the writing of the manuscript. All remaining
863 authors provided feedback on benchmark design, participated in the benchmark exercises (listed in
864 Table 2), and/or helped with revising the manuscript. V.L. additionally helped with the early tests
865 of benchmark problems; the other authors are listed alphabetically.

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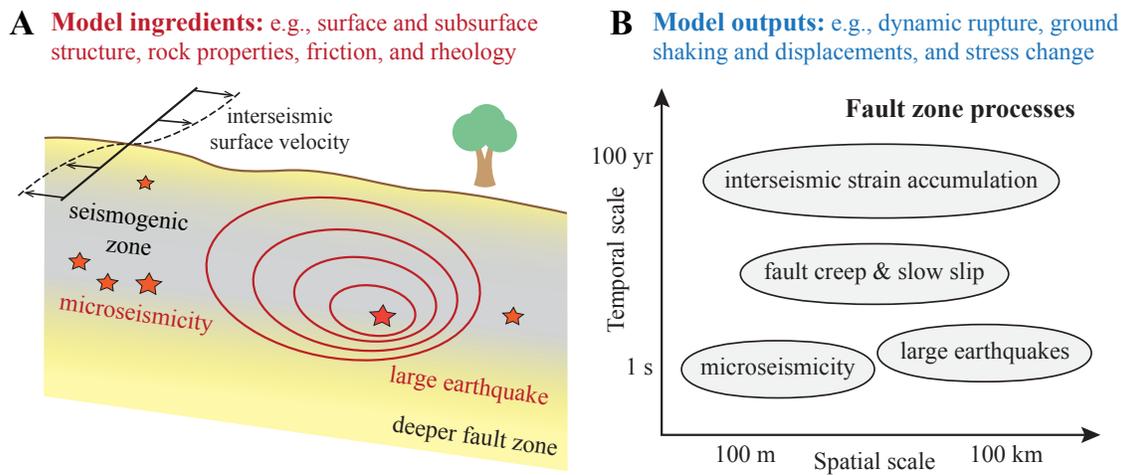


Figure 1. Main ingredients and outputs in 3D models of sequences of earthquakes and aseismic slip (SEAS).

(a) SEAS models incorporate the surface and subsurface structure, rock properties, friction, and rheology of a fault zone to simulate earthquakes and aseismic deformation. In the sketch of a strike-slip fault model, earthquake hypocenters are marked by red stars and rupture fronts of large earthquakes are shown as red contours. The seismogenic zone is colored in gray and aseismic fault zone in yellow. (b) SEAS models produce many outputs, including fault slip, off-fault displacements, and stress changes, which can be connected to observations of fault zone processes spanning a range of spatial and temporal scales, such as microseismicity, large earthquakes, fault creep, slow slip, and interseismic strain accumulation.

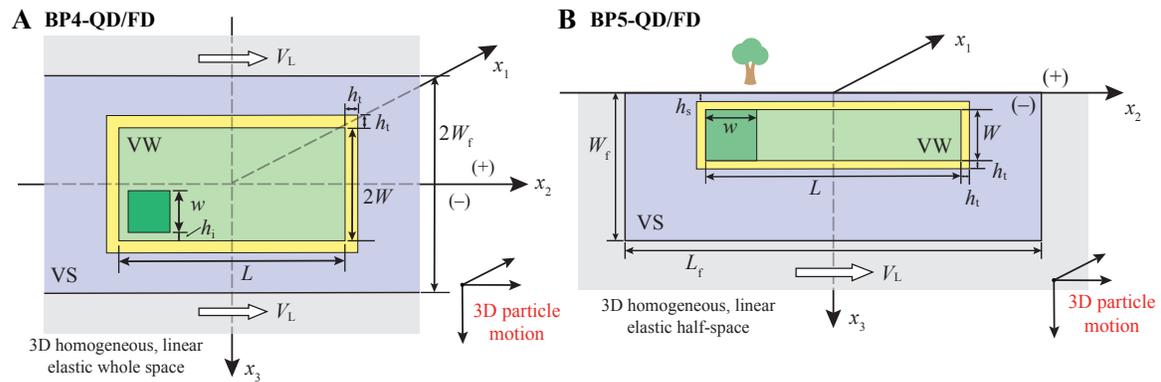


Figure 2. Two benchmark problems for 3D SEAS models. The benchmarks (a) BP4 and (b) BP5 consider 3D motion with a vertical planar fault embedded in a homogeneous, isotropic, linear elastic whole space and a half-space with a free surface, respectively. The fault is governed by a rate-and-state friction (RSF) law in the central region (non-gray colors) and assigned a constant rate at the boundaries (gray). The velocity-weakening (VW) region (light and dark green) is surrounded by a transition zone (yellow) and velocity-strengthening (VS) regions (blue). In the x_2 and x_3 directions, the sizes of the frictional domain and VW region are $(\infty, 2W_f)$ and $(L, 2W)$, respectively, for BP4, and (L_f, W_f) and (L, W) for BP5. 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. FD and QD in the benchmark names refer to fully dynamic and quasi-dynamic earthquake rupture problems, respectively.

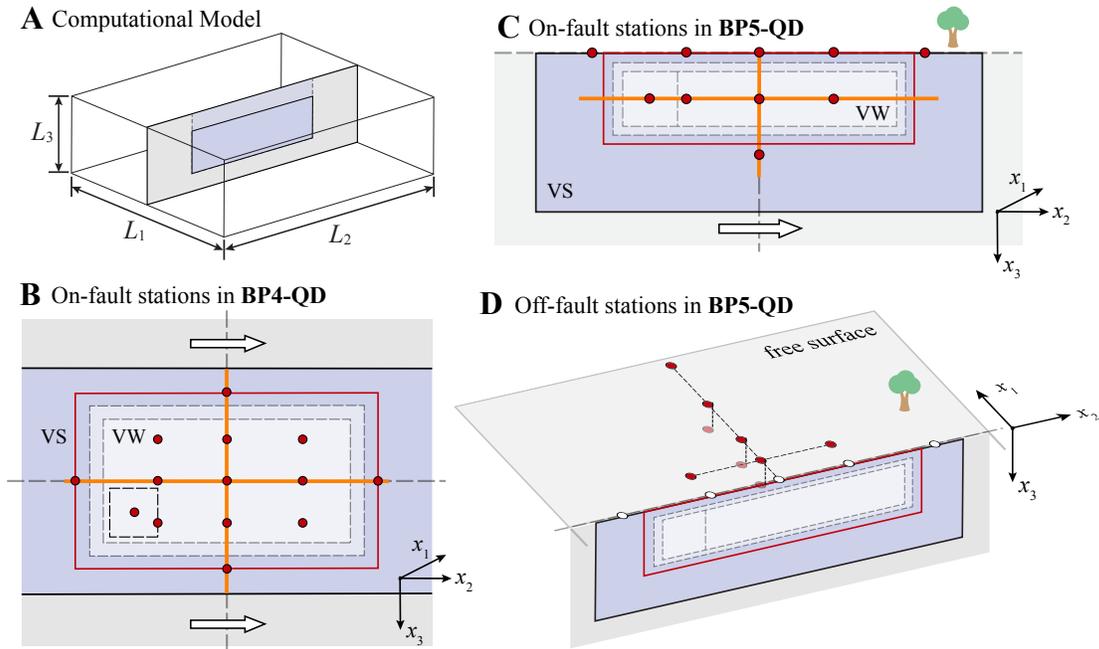


Figure 3. Computational model setup and simulation outputs for 3D SEAS benchmarks. (a) The fault-normal, along-strike, and along-dip dimensions of a computational model is denoted as L_1 , L_2 , and L_3 , respectively. Observation points, lines, and areas are shown for (b) BP4 and (c and d) BP5. Local time series are produced at (b and c) on-fault and (d) off-fault points (red). Profiles of slip and stress evolution are produced along cross-section lines (orange). The region outlined in red is used to compute time-dependent source properties and rupture front contours. Dashed rectangles indicate fault areas with different frictional properties.

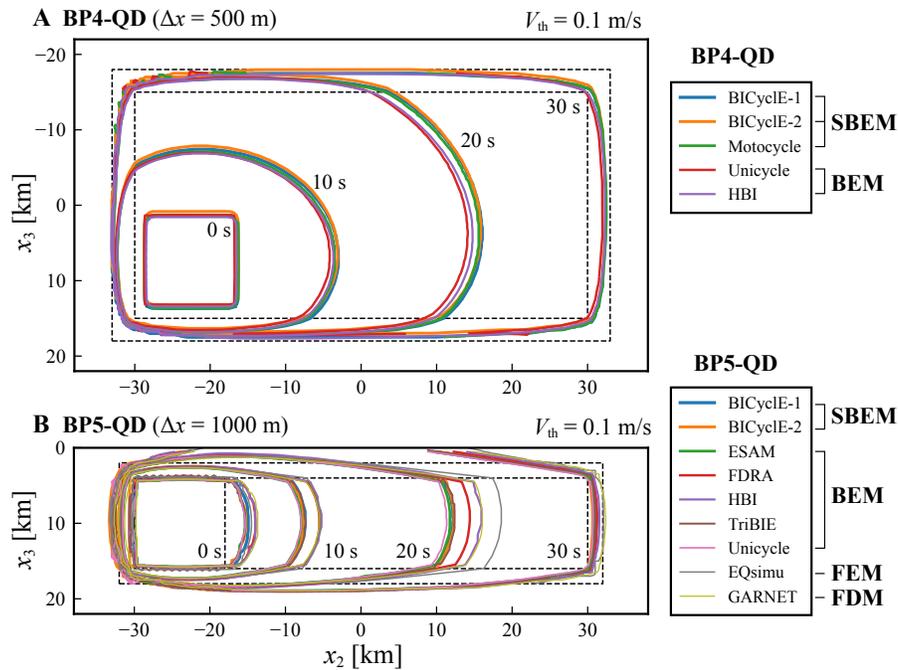


Figure 4. Rupture fronts of the first earthquake in BP4-QD and BP5-QD simulations with suggested numerical resolutions. The contours of rupture fronts are shown for simulations in (a) BP4-QD ($\Delta x = 500$ m) and (b) BP5-QD ($\Delta x = 1000$ m). The rupture front contours indicate 0, 10, 20, and 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.

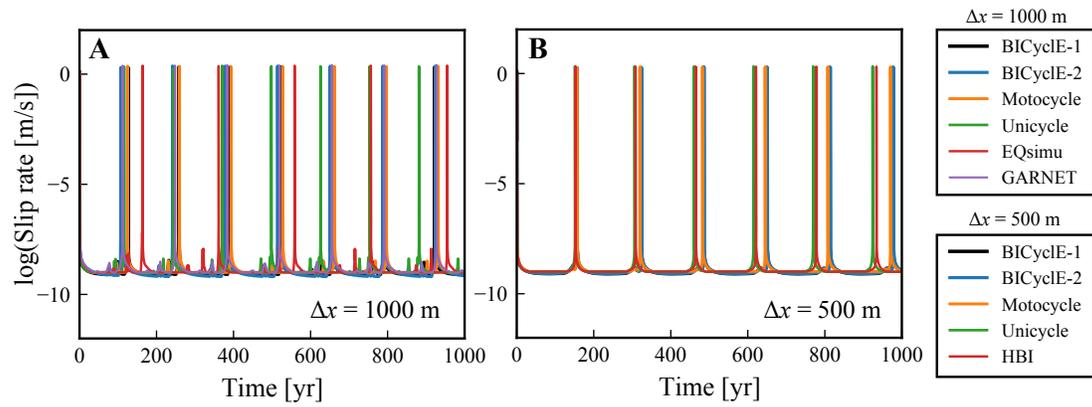


Figure 5. Time evolution of maximum slip rates in BP4-QD simulations. The time series of logarithmic maximum slip rates within the seismogenic zone are shown for simulations with (a) $\Delta x = 1000$ m and (b) $\Delta x = 500$ m. We use logarithms with base 10 and code names in legends in this and all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

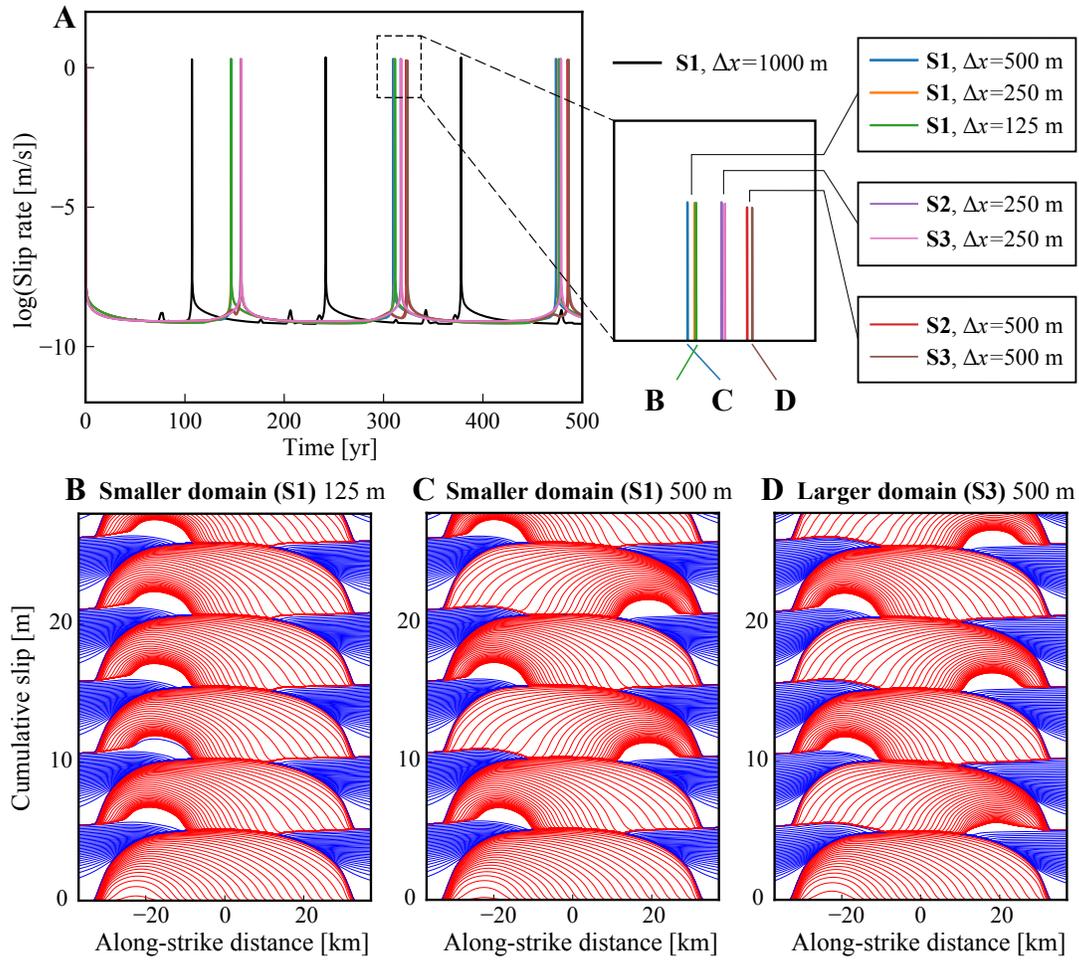


Figure 6. Effect of computational grid spacing and domain size on the self-convergence of SBEM simulations.

(a) Time evolution of maximum slip rates for a suite of BICycle-2 simulations with different grid spacings

($\Delta x = 125, 250, 500,$ and 1000 m) and domain sizes: $(L_2, L_3) = (120$ km, 90 km), $(240$ km, 180 km), or

$(480$ km, 360 km), denoted as S1, S2, or S3, respectively. Cumulative slip in the along-strike direction is plotted

every 1 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. The threshold slip rate for the

coseismic phase is $V_{th} = 0.01$ m/s.

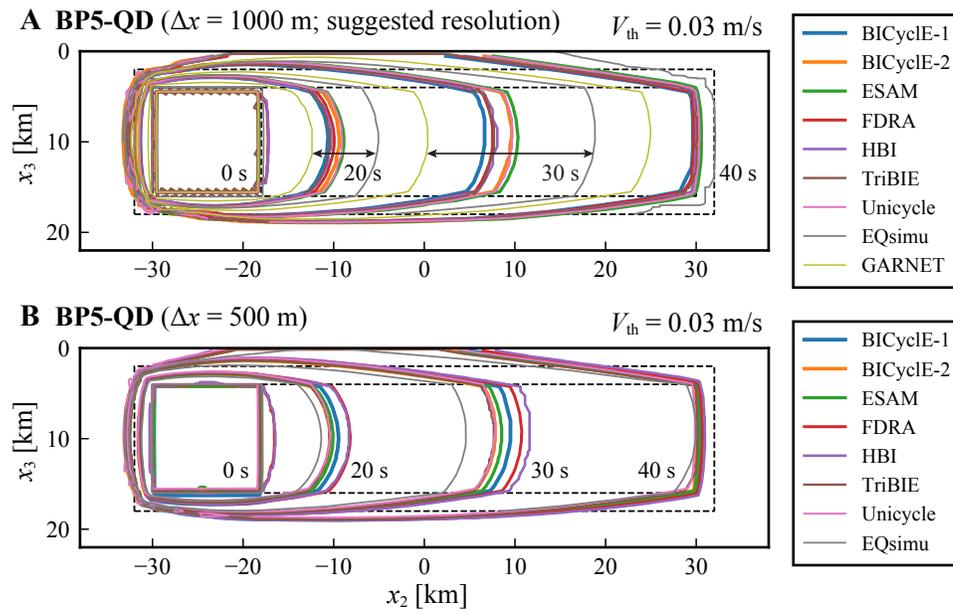


Figure 7. Rupture fronts of the first earthquake in BP5-QD simulations with different numerical resolutions. The contours of rupture fronts indicate 0, 20, 30, and 40 s after the earthquake initiation time in simulations with (a) $\Delta x = 1000$ m and (b) $\Delta x = 500$ m. The threshold slip rate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

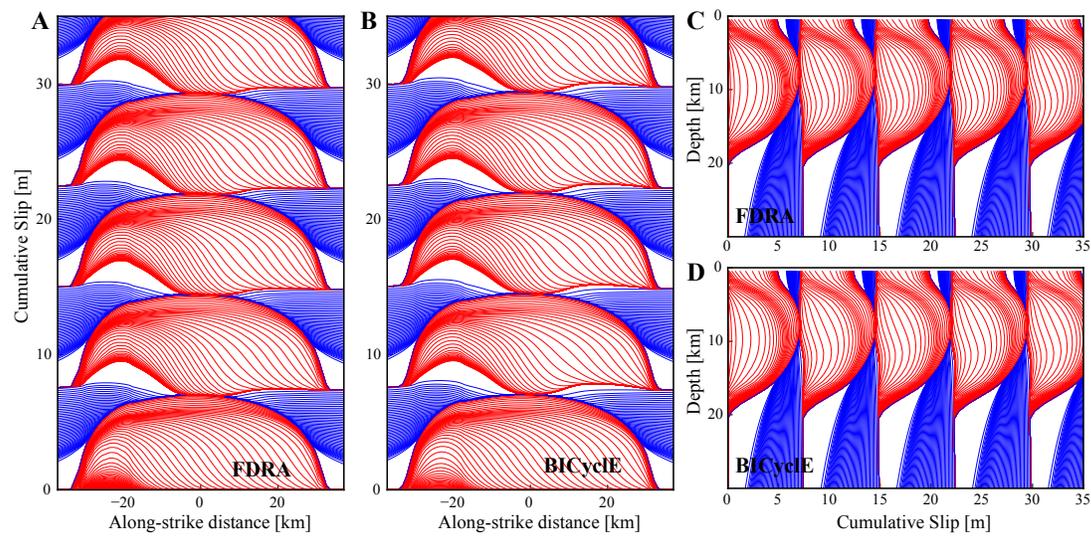


Figure 8. Fault slip evolution in selected BP5-QD simulations. Cumulative fault slip in two simulations ($\Delta x = 1000$ m) using FDRA and BICycleE is plotted along (a and b) horizontal ($x_3 = 10$ km) and (c and d) vertical ($x_2 = 0$ km) profiles shown in Figure 3. The seismic slip (red lines) is plotted every 1 s and aseismic slip (blue lines) is plotted every 5 yr, with the threshold slip rate $V_{th} = 0.01$ m/s.

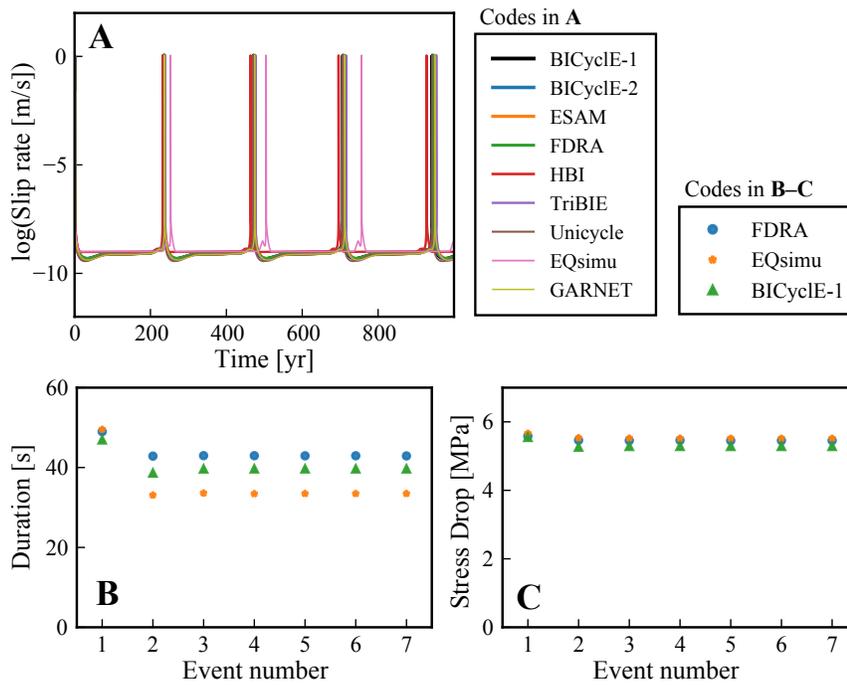


Figure 9. Long-term fault behavior and earthquake characteristics in BP5-QD simulations. (a) Time evolution of maximum slip rates in the seismogenic zone and (b) rupture duration and (c) stress drop for the first seven earthquakes are shown for simulations with $\Delta x = 1000$ m.

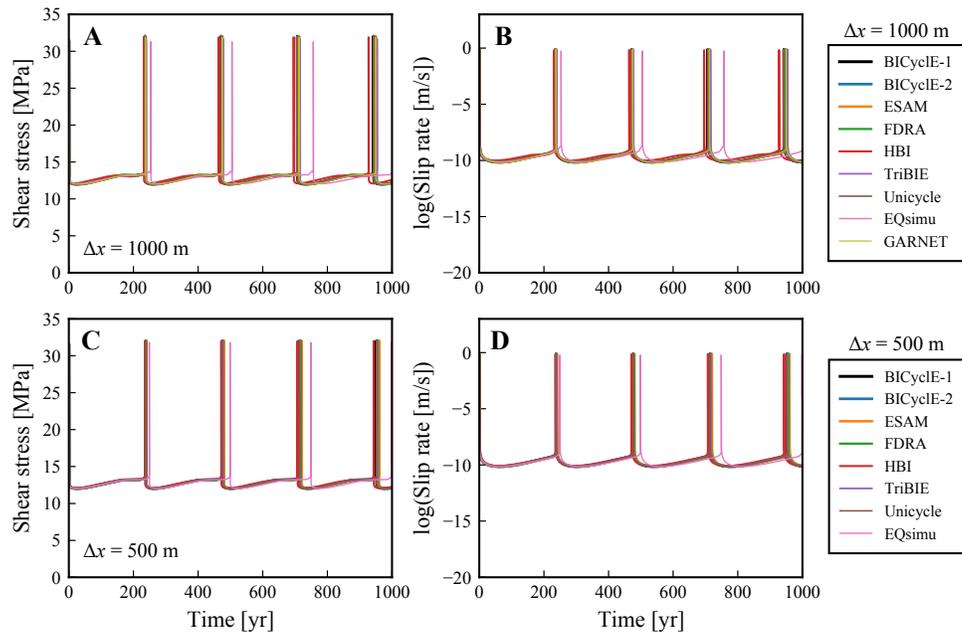


Figure 10. Long-term fault behavior at the surface in BP5-QD simulations. (a and c) Shear stress and (b and d) slip rates on the fault at the surface ($x_1 = x_2 = x_3 = 0$ km) in simulations with (a and b) $\Delta x = 1000$ m and (c and d) $\Delta x = 500$ m.

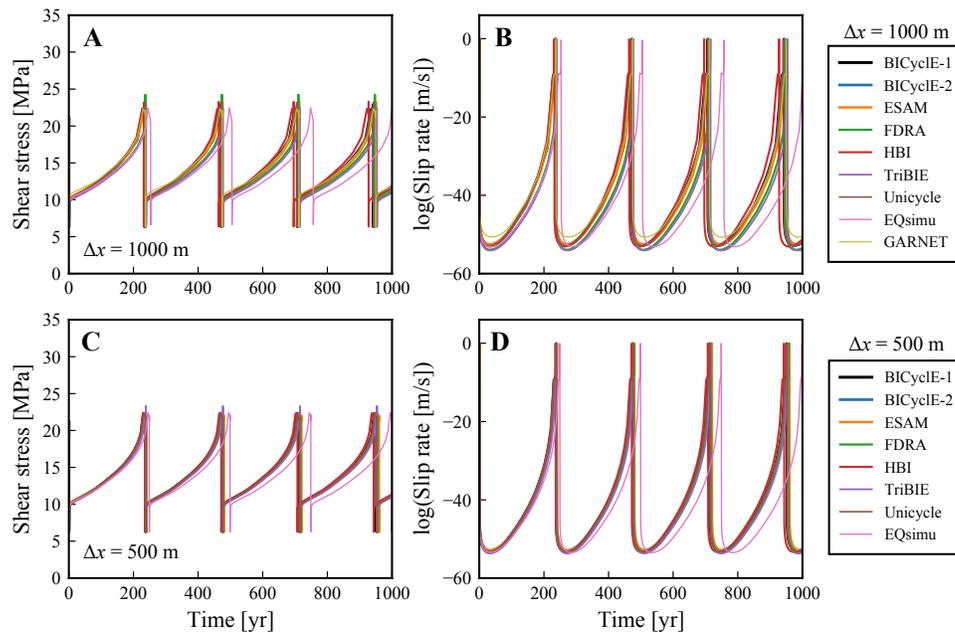


Figure 11. Long-term fault behavior at a seismogenic depth in BP5-QD simulations. (a and c) Shear stress and (b and d) slip rates on the fault at the mid-seismogenic depth ($x_1 = x_2 = 0$ km; $x_3 = 10$ km) in simulations with (a and b) $\Delta x = 1000$ m and (c and d) $\Delta x = 500$ m. Note that the range of vertical axes in panels b and d are different from those in Fig. 10.

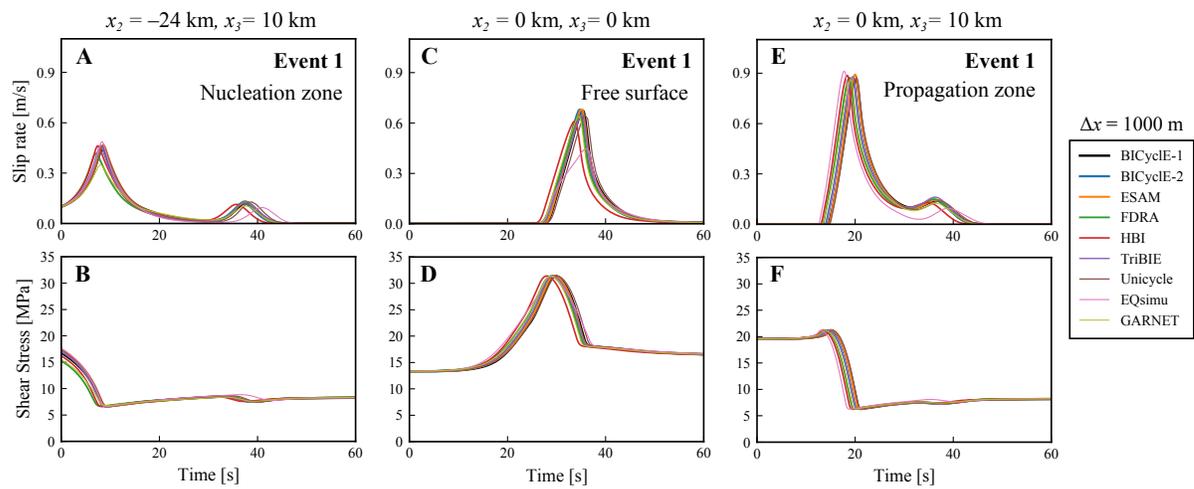


Figure 12. Coseismic rupture of the first event in BP5-QD simulations ($\Delta x = 1000$ m). Time evolution of (a, c, and e) slip rates and (b, d and f) shear stresses during the first earthquake are shown at different locations on the fault. Panels a and b refer to a point within the initial nucleation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

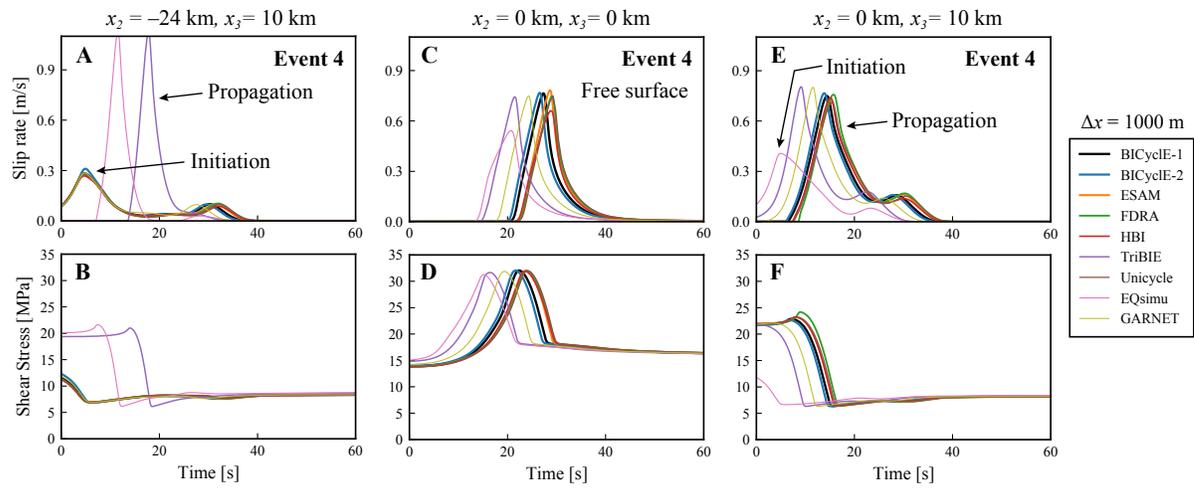


Figure 13. Coseismic rupture of the fourth event in BP5-QD simulations ($\Delta x = 1000$ m). Time evolution of (a, c, and e) coseismic slip rates and (b, d and f) shear stresses are shown at the same locations on the fault as in Figure 12. The discrepancy of TriBIE and EQsimu simulations with others are due to different rupture directions. We mark the distinct signals indicating the rupture initiation or propagation in panels a and e.

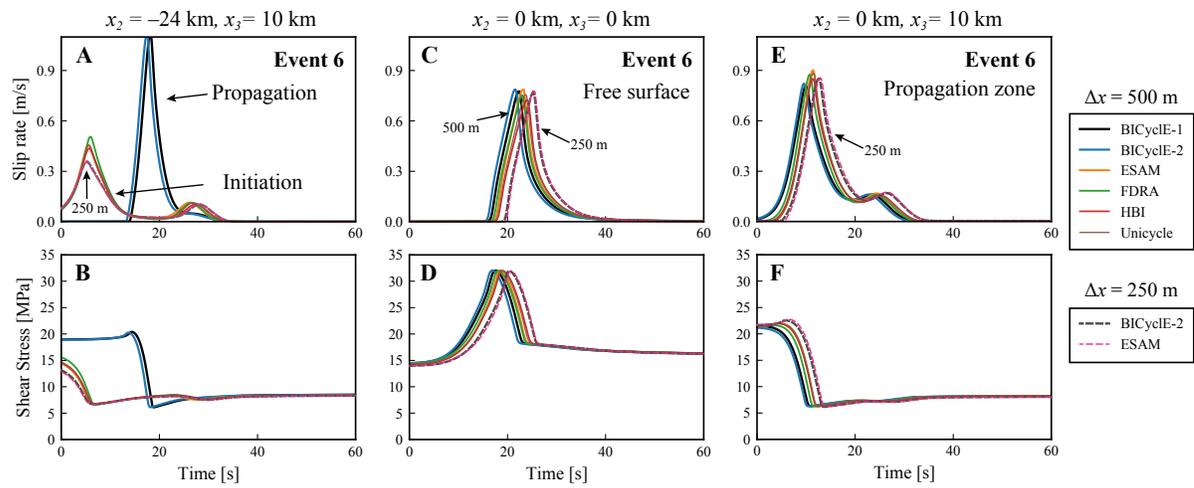


Figure 14. Coseismic rupture of the sixth event in BP5-QD simulations ($\Delta x = 500$ and 250 m). Time evolution of (a, c, and e) coseismic slip rates and (b, d and f) shear stresses are shown at the same locations on the fault as in Figure 12. We mark the distinct signals indicating the rupture initiation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

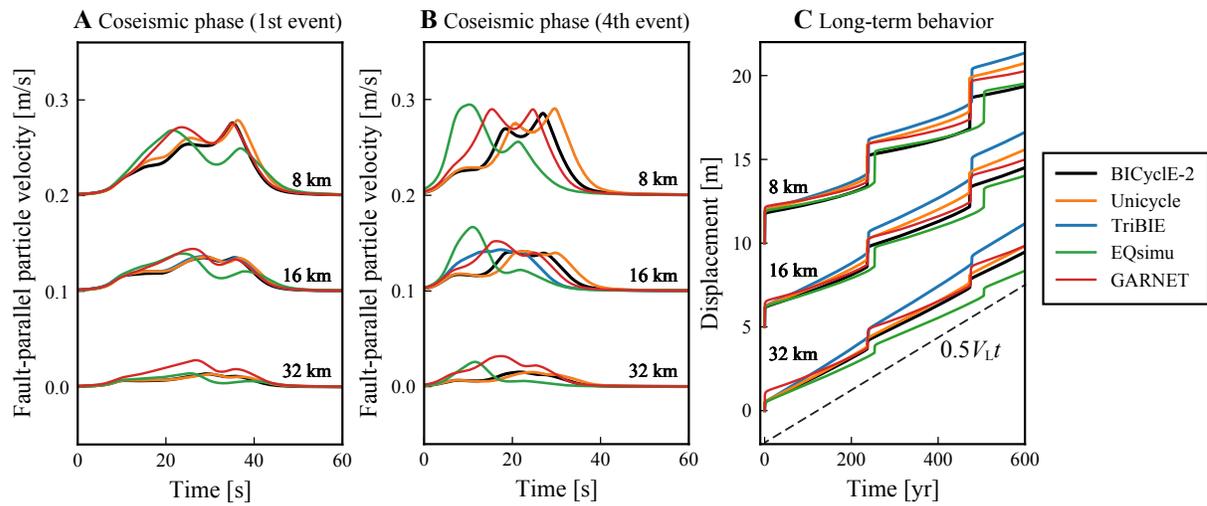


Figure 15. Off-fault ground displacements in BP5-QD simulations. Fault-parallel displacement rates v_2 during the (a) first and (b) fourth events, and (c) long-term displacement history are shown at three off-fault locations on the surface ($x_1 = 8, 16,$ or 32 km; $x_2 = 0$ km; $x_3 = 0$ km). The dashed 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.

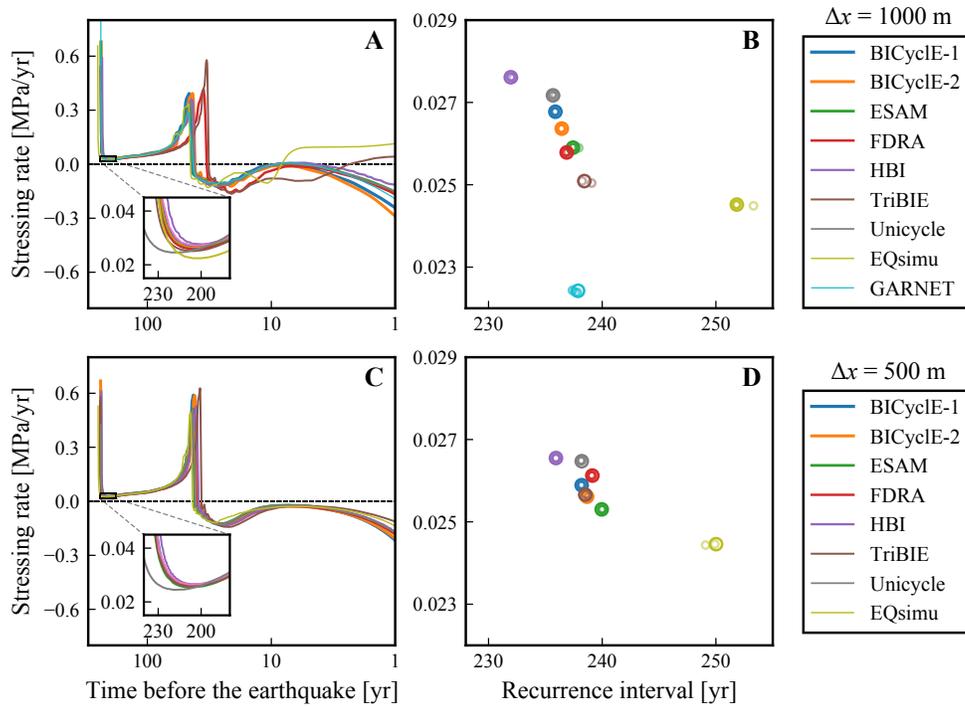


Figure 16. Interseismic stressing rate history and earthquake recurrence intervals in BP5-QD simulations. (a and c) Stressing rates at the mid-seismogenic depth ($x_2 = 0$ km; $x_3 = 10$ km) during the postseismic and interseismic periods before the sixth earthquake. (b and d) The minimum interseismic 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 simulated time, the fourth event from TriBIE and EQsimu is considered in panels c–d.

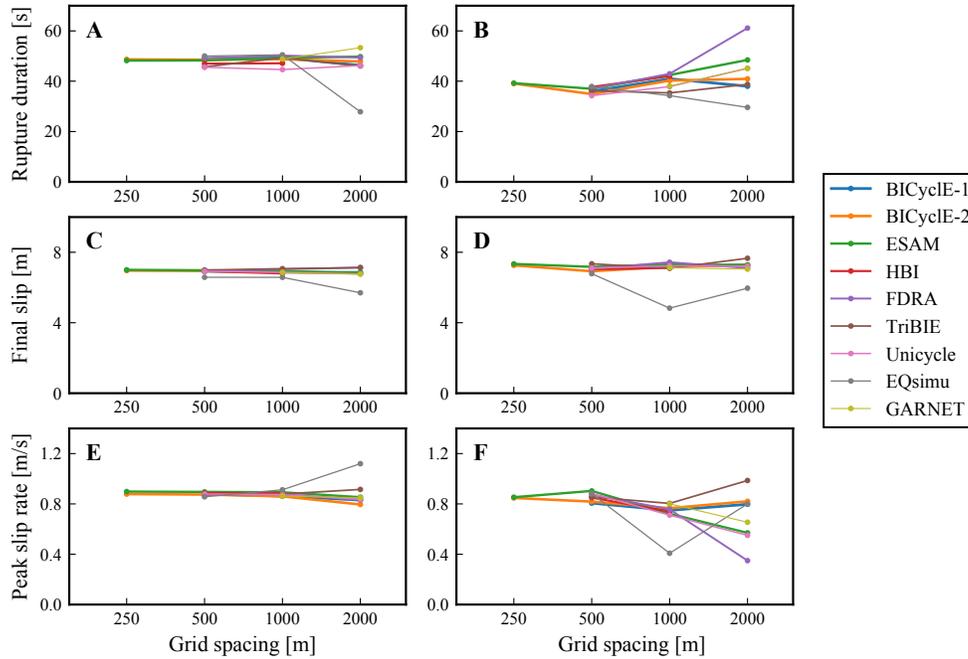


Figure 17. Comparison of earthquake characteristics in simulations with different resolutions. Coseismic rupture durations are shown for the (a) first and (b) sixth events in simulations with $\Delta x = 250, 500, 1000,$ and 2000 m, when available. (c and d) Coseismic slip and (e and f) peak slip rate 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	Symbol	Value in BP4	Value in BP5
Density	ρ	2670 kg/m ³	2670 kg/m ³
Shear wave speed	c_s	3.464 km/s	3.464 km/s
Poisson's ratio	ν	0.25	0.25
Effective normal stress	σ_n	50 MPa	25 MPa
Characteristic state evolution distance	D_{RS}	0.008 m	0.14 m/0.13 m ^a
Rate-and-state parameter, direct effect, VW ^b	a_0	0.0065	0.004
Rate-and-state parameter, direct effect, VS ^b	a_{max}	0.025	0.04
Rate-and-state parameter, evolution effect, VW & VS ^b	b_0	0.013	0.03
Reference slip rate	V^*	10 ⁻⁶ m/s	10 ⁻⁶ m/s
Reference coefficient of friction	f^*	0.6	0.6
Plate loading rate	V_L	10 ⁻⁹ m/s	10 ⁻⁹ m/s
Initial slip rate	V_{init}	10 ⁻⁹ m/s	10 ⁻⁹ m/s
Initial slip rate in prescribed nucleation zone	V_i	0.01 m/s	0.03 m/s
VW region, (half-)width ^c	W	15 km	12 km
VW region, length	L	60 km	60 km
VW-VS transition zone, width	h_t	3 km	2 km
Shallow VS region, width	h_s	-	2 km
Rate-and-state fault, (half-)width ^c	W_f	40 km	40 km
Rate-and-state fault, length	L_f	∞	100 km
Prescribed nucleation zone, width	w	12 km	12 km
Quasi-static process zone size	Λ_0	2 km	6 km
Nucleation size	h^*	12.4 km	12.5 km
Suggested grid spacing	Δx	500 m	1000 m
Final simulated time	t_f	1500 years	1800 years

^a The value used in the prescribed nucleation zone.

^b Parameters a and b for velocity-weakening (VW) or velocity-strengthening (VS) regions.

^c Half-width for BP4-QD and full width for BP5-QD.

Table 2. Participating SEAS codes and modeling groups

Code Name	Type	Simulation ^a (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>

^a The names of simulations displayed on our online platform.

Table 3. Model parameters in BP4-QD simulations

Code Name	Simulation Name	Grid Spacing (km) ^a	Domain Size (km) ^b	BC ^c
BICycle	jiang	1, 0.5	(192, 96, ∞)	P
	lambert	1, 0.5, 0.25, 0.125	(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 simulations submitted by each modeling group.

^b The total dimensions 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 and x_3 directions.

Table 4. Model parameters in BP5-QD simulations

Code Name	Simulation Name	Grid Spacing (km) ^a	Domain Size (km) ^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	2, 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 x_2 and x_3 directions, respectively.

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