2025 SCEC Project Final Report

SCEC Identifier	25273
Project Title	*Advancing Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS)*
Project Period	February 1, 2025 - January 31, 2026
SCEC Science Milestones Addressed	C1,2,3-1

Institutional Affiliation	**Investigators**
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Summary

Developing robust predictive models of earthquake source processes is one of the main SCEC goals. Research groups within the earthquake science community are contributing to this goal through the development of computational methods for simulating Sequences of Earthquakes and Aseismic Slip (SEAS). In SEAS models, the goal is to capture the interplay of tectonic loading (or strength changes from fluid pressure transients) and the associated aseismic fault slip—that ultimately lead to earthquake nucleation—and earthquakes (dynamic rupture events) themselves, and understand which physical factors control the full range of observables such as aseismic deformation, earthquake nucleation, ground shaking during dynamic rupture, recurrence times and magnitudes of major earthquakes. One of the significant challenges in SEAS modeling efforts arises from the varying temporal and spatial scales that characterize earthquake source behavior. Computations are further complicated when material heterogeneities, bulk inelastic responses, fault non-planarity, and their evolution with time and slip, are included. However, accounting for such complexity is widely recognized as crucial for understanding the real Earth and predicting hazards.

SCEC has supported community code exercises on verifying and validating spontaneous dynamic earthquake rupture simulations (*Harris et al.*, 2009; *Barall and Harris*, 2015; *Harris et al.,* 2018) and comparing earthquake simulators (*Dieterich and Richards-Dinger,* 2010*; Tullis et al.*, 2012). Dynamic rupture simulations have allowed us to investigate the underlying physics of what influences ground motion, but they are limited to single-event scenarios with imposed artificial prestress conditions and ad hoc nucleation procedures. In contrast, earthquake simulators can produce long-term earthquake sequences but often adopt semi-kinematic assumptions and are missing processes that could affect earthquake and fault interaction, such as stress transfer generated by dynamic waves, aseismic slip within fault segments, and inelastic deformation. SEAS models are needed to simulate longer periods of earthquake activity than single-event simulations but with the same level of computational rigor, while incorporating processes that are important over longer time scales. SEAS models better inform initial conditions and nucleation procedures for dynamic rupture simulations and provide physics-based approximations for larger-scale, longer-term earthquake simulators.

With SCEC support this past year, we have continued our efforts to lead the community code verification exercises for SEAS models. Our main progress and achievements are:

- We developed new benchmark problems on 3-D fluid injection (BP8) and dipping fault with depth-dependent normal stress (BP9) that we plan to release in spring 2026.
- We conducted a public survey to gauge interest and readiness for future benchmark problems (BP10 & BP 11) among potential participants.
- We presented our results at the 2025 SCEC Annual Meeting and 2025 EGU Conference.
- We collected new results and continued comparisons of results for BP7 (a 3-D repeating earthquake problem).
- We started a collaboration with CRESCENT to utilize an improved and robust data-sharing platform for code verification (e.g., https://det.cascadiaquakes.org/?benchmark_id=ttpv1) for future benchmarks, starting with BP8.
- We welcomed a new member to the SEAS leadership team, Taeho Kim.

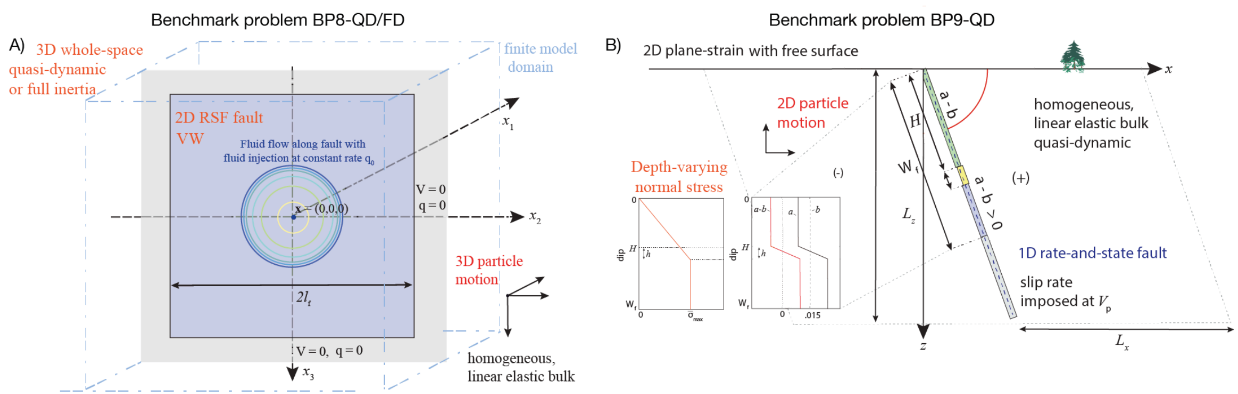

Figure 1. A) BP8 considers a 2-D planar fault embedded in a 3-D homogeneous, linear elastic whole-space where fault slip is initially induced by the injection of fluid at the center of the fault. The fluid injection is modelled either as a Gaussian source (BP8-QD-GS) or with a Peaceman well (BP8-QD-PW). B) BP9 considers a 1-D dipping fault with a free surface that is loaded at a constant slipping rate from below. Previous benchmark BP3 considered uniform normal stress along the fault whereas BP9 considers more realistic depth-variable normal stress along the fault. New model components are highlighted in orange.

BP8-QD-GS/PW: 3-D problem studying fluid effects on faulting with different treatments of fluid injection.

This benchmark focuses on fault slip in 3D that is triggered by pore fluid pressure changes that are variable in time and space. The problem consists of two variations of the fluid pressure perturbation: One where the injection rate is distributed as a Gaussian source that exponentially decays in strength as a function of the radial distance from the origin (BP8-QD-GS) and another where a realistic wellbore with a finite well radius is treated through the Peaceman well formulation (BP8-QD-PW). The former variation is inspired by natural fluid sources that produce fault slip such as pressure diffusion from a fault valving event in volcanic or geothermal regions or subduction zones. The latter variation (Figure 2) is relevant for subsurface fluid injections such as in the context of geologic carbon sequestration, enhanced geothermal systems, wastewater disposal, and geologic hydrogen. Both variations regularize the singularity of the pressure field that would occur at the injection location due to a point source and avoid mesh-dependence. Both variations are highly relevant for problems of interest in the earthquake modeling community. The remote shear and total normal stress are held fixed, so that only one episode of aseismic slip will occur. We have also provided analytical solutions for verification of numerical implementations of pressure diffusion in 2-D space.

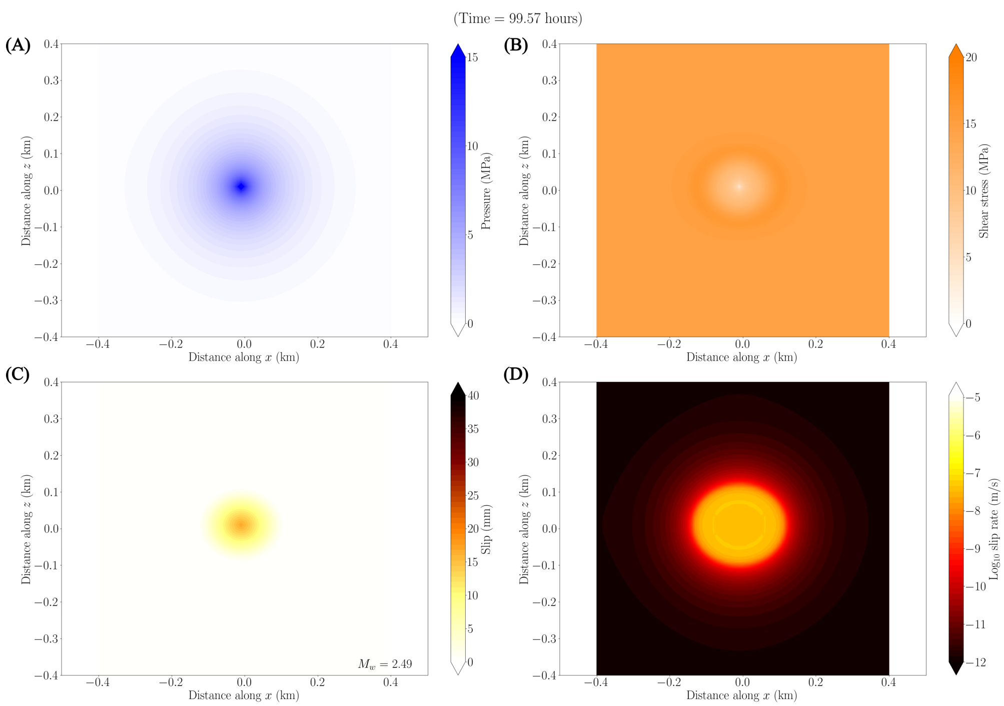

Figure 2. Contour plots along the fault surface for the (A) pore pressure, (B) shear traction, (C) cumulative slip, and (D) slip rate at the time of the maximum pressure change from a preliminary simulation of BP8-QD-PW. The Peaceman well model regularizes the singularity of the pressure field at the injection point (A) by distributing the injection rate across a finite wellbore. The Peaceman model is a subgrid-scale model designed for wellbores that are much smaller than the cell size used for pressure diffusion and fault slip modeling.

Efficient & Robust Data-Sharing: A novel collaboration with CRESCENT DET

We began a collaboration with CRESCENT's Dynamic Rupture, Earthquake Cycle, and Tsunamis Working Group (DET) for an improved data-sharing platform for SCEC SEAS benchmark simulations. This collaboration between SCEC and CRESCENT allows us to leverage the advanced data-sharing platform developed by Loïc Bachelot of CRESCENT (Figure 3), which will facilitate and safeguard the sharing of simulation data. Unlike previously, submission files no longer have to be uploaded individually, and instead can be compressed into a single zip folder. The data-sharing platform will then automatically recognize files by their filenames to be chosen for visualization by the user. The platform allows the visualization and comparison of data from different modelers using the online plotting tools, without direct access to the raw data. The data visualization tool is not only available for time series data acquired from single points on the numerical grid (Figure 3), but also evolutions of variables in space and time, using the contour plotting tool (Figure 3). Overall, the utilization of the advanced data-sharing platform will greatly facilitate data comparison and analysis, and save valuable time for participants in uploading their simulation data, so that they may focus their efforts on code development and testing. Platform capabilities are explained in detail in a recent submission to Seismica (Bachelot et al., 2026).

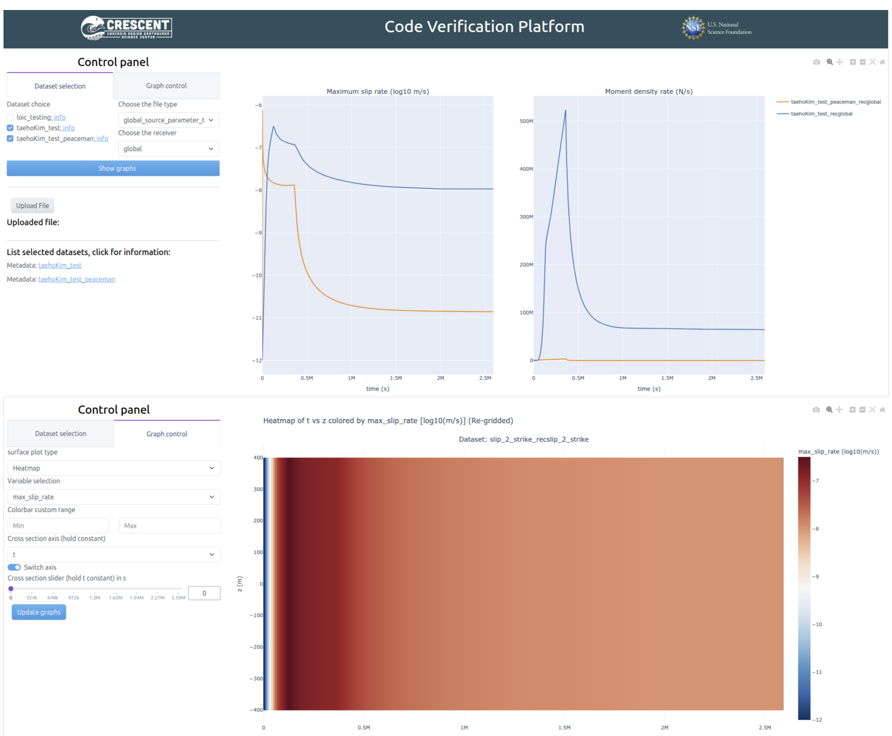

Figure 3. The CRESCENT code verification platform (Bachelot et al., 2026) allows time series data visualization (top row, comparing the maximum slip rate and total moment density rates for BP8-GS and BP8-PW), and the evolutions of variables in space and time, using the contour plotting tool (bottom row, showing slip rate profile along a strike-line in time and space). The data-sharing platform is easy to use, efficient, and safe.

BP9: Dipping fault with depth-variable normal stress

BP9 extends BP3, a previous benchmark problem for earthquake cycles on dipping faults. BP3 considered both thrust and normal faults, but assumed constant, depth-independent effective normal stress on the fault. Modeling groups that modified this benchmark for research applications by accounting for depth-dependent effective normal stress encountered numerical challenges, such as instabilities near the free surface and reductions in time step that prevented integration through the interseismic period. These were ultimately traced to numerical stiffness, a situation where the maximum time step required for stability of an explicit time-stepping method is much smaller than the time step required for an accurate solution. Stiffness is a well-known feature of certain equations, such as the diffusion equation, but had not previously been noted for SEAS simulations, to the best of our knowledge. BP9 is being designed to draw attention to this challenge, which remains unsolved. We are planning several variants of BP9 in which a lower bound is placed on effective stress when evaluating the fault shear strength. If that bound is large, then large time steps are stable and there are no issues when integrating through the interseismic period (as in previous benchmarks). However, as the bound is reduced, the maximum time step becomes smaller, ultimately to the point where it becomes infeasible to integrate through the interseismic period. It is likely that a fully or partially implicit time-stepping method will be required. As of March 2026, we are finalizing details of BP9 and plan to release it later this spring.

Survey for Future Benchmark Problems (BP10 & BP11)

The survey for future benchmark problems gauged interest and readiness for 3 potential problems that we may consider for BP 10 & BP 11: 1) Two-way coupled hydromechanics with feedback mechanisms from fault slip to pressure diffusion, such as dilatancy/compaction (inelastic porosity evolution with slip), slip- and time-dependent evolution of permeability and specific storage (fault-valving and healing) and shear heating, 2) Shear zone viscous flow where the friction law is replaced with a more complex constitutive law, that accounts for the combined response of a thin viscous shear layer of fixed width, governed by a flow law, within which a frictional fault, governed by a friction law, is embedded, and 3) Non-planar fault geometry that tests the effect of a seamount on earthquake nucleation and the propagation of seismic or aseismic slip events. We received 25 responses with strong levels of interest to participate in all 3 problems (88%, 84%, and 92%, respectively). The survey indicated that there is significant readiness among the community members to participate in the potential benchmarks, with a limited portion indicating that the problems would not be feasible with their current numerical framework (12%, 12%, and 20%, respectively). Finally, most survey responses indicated that all three topics are either important or very important scientific problems. Participants also suggested future benchmark problems: heterogeneous frictional properties on planar faults, boundary conditions specified along fixed domains, the use of physics-based constitutive laws for friction, and viscoelasticity in the bulk. Additionally, participants provided specific details regarding what implementations would be necessary to participate in the potential future benchmarks. This valuable input from the community will inform us to better design relevant and tractable benchmarks in the future.

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