February 24, 2026

Final Report for SCEC Award #25347

Submitted by Ruth Harris and Michael Barall
to the Statewide California Earthquake Center (SCEC)

A Dynamic Rupture Workshop to Improve our Understanding of Fault Friction

December 2, 2025

(SCEC Project #25347)

Co-Principal Investigators:

Ruth Harris and Michael Barall
(U.S. Geological Survey)

On December 2, 2025, we convened in Zoom the Statewide California Earthquake Center's (SCEC) Dynamic Rupture Technical Activity Group (TAG) workshop "*A Dynamic Rupture Workshop to Improve our Understanding of Fault Friction*". **94 people** participated, in addition to three more people who sent pre-recorded talks but were unable to join us in Zoom that day. More than one-half of our workshop participants were students or postdocs, and the group included scientists from institutions in **14 countries** (USA, Canada, China, Czech Republic, France, Germany, Israel, India, Italy, Japan, Mexico, New Zealand, Pakistan, Switzerland).

Our workshop included **27 talks** along with many opportunities for discussion. Ten were invited longer talks, two were invited shorter talks, and 15 were 100-second, 1-slide lightning talks.

The detailed workshop agenda is on page 8 of this report, and many of the speakers' slides and lightning-talk videos can be found on our SCEC workshop's website:
https://www.scec.org/events/2025-scec-dynamic-rupture-workshop/
Many thanks to Edric Pauk and Tran Huynh for helping to make this event successful.

Our group's workshops are now in their twenty-first year. Over the years we have discussed and learned about science discoveries and computational requirements needed to produce spontaneous (dynamic) earthquake rupture simulations. We have carefully tested our codes using verification exercises and incrementally implemented new model features so that the codes can usually reproduce the results of other codes using the same assumptions. For more information about how dynamic rupture simulations work, please see **Figure 1**, and especially, **Ramos et al. (2022)**.

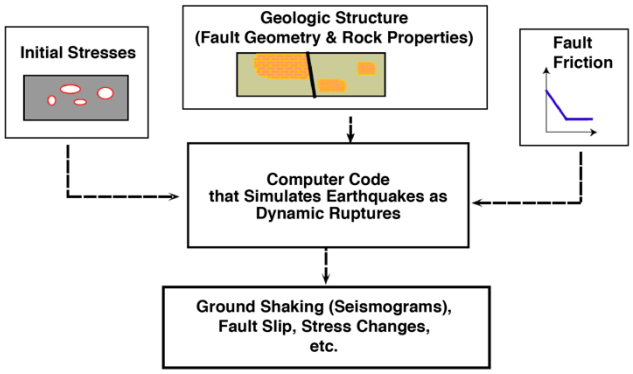

Figure 1. (Lightly modified Figure 1 from Harris et al., 2018). Dynamic rupture simulations require assumptions about the on-fault initial stresses (and the off-fault initial stresses, if the medium is inelastic), the fault geometry, the rock properties, and a failure criterion that describes how fault friction works. These physics-based computer simulations can be used to produce many different types of results, including fault slip, ground and sub-surface shaking, stress changes, and heat generation. Please see Ramos et al. (2022) for more details. In this 2025 workshop, we concentrated on the fault friction "ingredient" depicted in the upper right part of the figure.

The focus of this year's workshop was coseismic fault friction. Our codes can implement many friction constitutive relations, but determining which friction framework is most appropriate for real faults remains unsolved. With this workshop, we heard the newest thinking about coseismic

friction mechanisms in general, as well as detailed observational evidence. In addition, the overviews from related SCEC groups described those groups' recent accomplishments, and the lightning talks, which were offered as an opportunity to every workshop registrant, highlighted a range of new results related to dynamic rupture simulations.

Overview of Workshop Presentations

Ruth Harris (U.S. Geological Survey, USGS) began the workshop by welcoming the participants, particularly noting that some were joining the Zoom meeting from distant locations, during a variety of times of day and night. She highlighted Edric Pauk's (SCEC) contributions to the workshop, noting his conscientious preparation and helpful guidance resulting in a seamless and successful science Zoom-gathering. She then introduced and briefly summarized how dynamic rupture simulations work, for the benefit of workshop attendees who were not yet dynamic rupture modelers. Harris encouraged everyone to read the publication by **Ramos et al. (2022)**. The 2022 paper provides information about dynamic rupture modeling and serves as a valuable resource and introduction to the field.

Harris described how the SCEC-USGS Dynamic Rupture Code Verification Group (please see the group's website https://strike.scec.org/cvws/) has successfully verified that many dynamic rupture codes' simulation results are reproducible for a variety of 'ingredients', i.e., the input assumptions about 1) the initial stresses, 2) the fault geometry, 3) the rock properties, and 4) the fault friction. She then reminded everyone that there are still significant unknowns within each of these assumptions, particularly the fault friction ingredient. When registering for the workshop, each participant was asked about their favored fault friction mechanisms. In one of her presentation slides (**Figure 2**) Harris summarized the workshop participants' answers, showing that both slip-weakening and rate-and-state-dependent friction were most popular, but that some preferred these two formulations not on their own, but with added features. She also noted that at least one participant commented that the simple fault friction mechanisms often assume that frictional sliding is occurring on a simple planar surface, whereas coseismic deformation most likely occurs in a complex 3D zone.

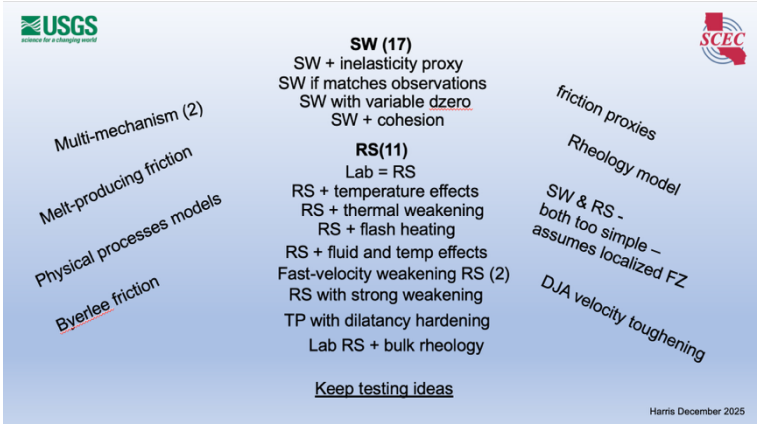

Figure 2. A slide from Harris's presentation showing the friction preferences the participants submitted when registering for the workshop. SW is slip-weakening, dzero is slip-weakening critical distance, RS is rate-and-state, TP is thermal pressurization, FZ is fault zone, DJA is Dudley Joe Andrews.

Harris next described the agenda for the workshop (please see page 8 of this report).

Following Harris's presentation, the participants introduced themselves, in the Zoom chat.

The next speaker was **Monica Barbery** (Brown University), who gave a comprehensive overview talk about frictional weakening mechanisms, and the observational evidence, primarily from lab experiments, in favor of each. The mechanisms she focused on included thermal pressurization of pore fluids, flash heating of asperities, viscous flow, and melt lubrication. She noted that there are also other possibilities, including mineral dehydration, mineral decarbonation, silica gel lubrication, nanoparticle lubrication, and elastohydrodynamic lubrication.

Alexis Ault (Utah State University) then summarized the September 2025 SCEC Crustal Rheology Model (CRM) workshop she co-led (Ault et al., 2025), and discussed how friction information might be included in a CRM database. Alexis also introduced new work on the rupture zones of the 2023 large-earthquakes in Turkiye.

Eric Burdette (USGS) talked about his innovative work using lasers to measure stress drop and fault slip in a rock mechanics laboratory setting, in addition to connections to earthquake and fault zone energy partitioning.

The workshop next featured eight 1-slide, 100-second lightning talks by **Zhiwei Wang** (CNRS) who talked about the onset of fault instabilities observed in the lab versus those inferred at Bedretto and UtahFORGE field sites, **Lav Joshi** (Charles University) who showed that dynamic rupture complexity explains the variability in earthquake source radiation patterns, with smooth models being unable to reproduce observed directivity, **Amy Lu** (McGill) who talked about the interactions between slow slip events (SSE's) and earthquakes in earthquake cycle models, **Srisharan Shreedharan** (Utah State University) who presented about lab experiments including the effects of a range of fault gouge clay content, **Baoning Wu** (UCSD) who talked about the effects of fault area contact and its connection to rate-and-state dependent friction formulations, **Gabrielle Hobson** (UCSD) who presented about the use of morph meshing to simulate fault geometry variation and its effect on surface displacement, **Peng Zhai** (U Michigan) who talked about how spontaneously generated fault damage helps control earthquake size, and **Jeremy Wong** (UCSD) who presented about how dynamic effects, rather than heterogeneous friction and stress distributions, are what controls megathrust earthquake complexity.

After a short break, the workshop continued with three more full-length talks:

Jun Young Song (Cornell University) presented his work on laboratory results for how faults heal and the effects of fault asperities, based on a model where the fault surface consists of velocity weakening patches and velocity strengthening patches, simulated using Teflon for the velocity strengthening patches and PMMA (plastic material) for the velocity weakening patches. In a comparison with numerical computations, he also showed that the loading rate determines if slip patches (and foreshocks, mainshocks, aftershocks) rupture together or independently.

Yuval Tal (Ben Gurion University) talked about work he had conducted with Nir Badt studying the interplay between geometrical fault roughness and fault friction, particularly how the effectiveness of thermal pore-fluid pressurization is affected by fault roughness, stress heterogeneities, .and hydraulic diffusivity.

Eric Ferre (New Mexico State University) presented a detailed view into pseudotachylytes, including the evolution of the science community's ideas about how and why pseudotachylytes form, and what they mean for fault friction behavior. He also provided explanations for why they are not always observed in fault zones, but showed that when they are observed, they are indicators that fault slip did occur. Interestingly, he also provided evidence that pseudotachylytes can be used to determine focal mechanisms, and perhaps, fault slip direction.

After a break, we next heard two more invited talks. Both were from the perspective of laboratory experiments and what they can teach us about how fault friction works.

Sara Beth Cebry (USGS) talked about her new work in the USGS rock mechanics laboratory investigating fault zone evolution. She started with pre-existing fault stepovers in a sandstone sample, then examined how the rock deformed when shear was applied. The fractures transformed from their original configuration of two separate faults separated by unbroken rock, into one continuous longer fault.

Tamara Jeppson (USGS) talked about how fault strength evolves under hydrothermal conditions. She found that the evolution depends on multiple parameters including time, temperature and chemical composition, with different processes acting at different time scales and temperatures. This information could be used to better understand the initial conditions at the beginning of dynamic rupture.

Our workshop continued with the presentation of seven more 1-slide, 100-second lightning talks, this time by **Di Deng** (CUHK) who talked about how to use arrival time differences at seismic stations to identify the occurrence of supershear rupture (with application to the 2023 Kahramanmaras, Turkiye earthquake), **Zeyu Lu** (USTC) who talked about the effect of an across-fault material contrast on stepover jump distances, and **Yuto Sasaki** (University of Osaka) who talked about his work to explain the difference between slow and regular earthquakes. His experimental results simulated a gouge layer, and the choice of gouge material (soft hydrogel versus rigid glass beads) determined the nature of the resulting slip. **Betsy Madden** (San Jose State University) talked about her work simulating dynamic rupture on some San Francisco Bay area faults and her work comparing observed versus modeled energy budgets for the 2004 Sumatra earthquake and a Cascadia scenario earthquake, **Duo Li** (Earth Science New Zealand) presented about how large dynamic rupture simulations demonstrate that rupture directivity can affect seismic hazard, **Alice Gabriel** (UCSD) talked about 3D nonlinear damage and its effects on propagating ruptures, including rupture jumping and ground motions, along with new work to infer the parameters using Bayesian inversion, and **Julian Lozos** (Cal State Northridge) discussed his dynamic rupture simulations testing the effects of creeping fault patches and determining how and when creeping patches might stop earthquakes from continuing to rupture.

The last three invited talks of the day were about the design and results from a Cascadia Region Earthquake Science Center/ Statewide California Earthquake Center (CRESCENT/SCEC) earthquake and tsunami code verification exercise, and about SCEC verification and validation technical activity groups.

Fabian Kutschera (UC San Diego) presented the CRESCENT dynamic rupture/tsunami benchmark exercises TTPV1 and TTPV2. These two exercises were designed by starting with the SCEC shallow-dip benchmark TPV36, but then the two exercises added the all-important water layer, to create a fully coupled earthquake-tsunami model. In TTPV1 the seafloor is planar, while in TTPV2 it has some topography. Fabian also introduced the new CRESCENT code comparison platform, and results from the modelers.

Valére Lambert (Apple) talked about the Simulations of Earthquake Sequences and Aseismic Slip (SEAS) project. The SEAS group benchmarks the codes used to simulate earthquake cycles and is finding relatively good qualitative agreement among the code results, when the assumptions are implemented in a similar manner. The group is continuously moving forward with new benchmarks "BPx" and incrementally adding complexity to the simulations. He presented the description and results for BP6-QD-A/S/C (QD=quasi-dynamic, FD=fully-dynamic, A/S=aseismic slip, C=constant friction coefficient), which models fluid-induced aseismic transients. The SEAS group's current work includes the exercise BP7-QD/FD-A/S, which involves repeating earthquakes and aseismic transients. Future benchmark BP8-QD/FD will be a 3D problem with fluid-induced aseismic slip along with dynamic rupture, and BP9-QD will be a 2D problem with depth-varying effective normal stress on dipping fault geometries.

Rachel Abercrombie (Boston University) gave an update of progress by the Stress Drop Validation Project. The goal of this project is to figure out how to robustly measure an important earthquake source parameter, "spectral stress drop", the corner frequency of the source spectrum, which is valuable for understanding how high-frequency ground motion is generated. To accomplish their goal, the group examined a large set of aftershocks of the 2019 M7.1 Ridgecrest, California earthquake. They found that different methods used by different sets of investigators sometimes produced different results, but that sometimes this was dependent on the magnitude of the aftershock. A future goal of the group is to use simulated data and determine its spectral stress drop. She also noted that recent publications include an article in Seismica and a special issue of the journal BSSA.

Wrap-up and Discussion

During the discussion at the end of the workshop, Harris mentioned that in November she submitted to SCEC a proposal for a 2026 dynamic rupture workshop focused on collecting the "ingredients" to simulate large-great earthquakes nucleating in the Parkfield region, with a hoped-for 2027 follow-on workshop providing the dynamic rupture results. She also mentioned that in November, she submitted a Letter of Intent to continue the Dynamic Rupture Technical Activity Group, with the group's newly proposed goal of simulating large earthquakes in California using dynamic rupture simulations.

Harris next returned to the friction topic. She reminded everyone about the answers provided by the participants before the workshop, specifically their favored fault friction mechanisms to use in dynamic (coseismic) rupture simulations (**Figure 2**). She then asked the group if there were any proposed friction mechanisms that people might now be comfortable discarding, in favor of other ideas, so as to narrow the range of friction options from which dynamic rupture modelers must choose. The reply was that none of the presented friction frameworks were ready to be discarded outright, but instead, the most appropriate friction choices depend on the fault setting, and the earthquake-model being simulated. The workshop ended on a high note, and a reminder that we still have more to research and discover.

Acknowledgments

Thank you to Fred Pollitz and Rob Graves for thoughtful U.S. Geological Survey internal reviews of this report, and to Edric Pauk and Tran Huynh for much appreciated workshop guidance. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Some References

Ault, A., S. Barbot, C. Seyler (2025), SCEC 25133 Workshop report: Integrating friction into the Community Rheology Model, https://files.scec.org/s3fs-public/reports/2025/25133_report.pdf?2dKd8LLU8I.ebPZbmehIxIpv9u2wJ0g1 (last accessed Jan. 28, 2026)

CRESCENT Dynamic Rupture, Earthquake Cycle, and Tsunamis Working Group: https://cascadiaquakes.org/det/

Harris, R.A., M. Barall, B. Aagaard, S. Ma, D. Roten, K. Olsen, B. Duan, B. Luo, D. Liu, K. Bai, J.-P. Ampuero, Y. Kaneko, A.-A. Gabriel, K. Duru, T. Ulrich, S. Wollherr, Z. Shi, E. Dunham, S. Bydlon, Z. Zhang, X. Chen, S.N. Somala, C. Pelties, J. Tago, V.M. Cruz-Atienza, J. Kozdon, E. Daub, K. Aslam, Y. Kase, K. Withers, and L. Dalguer (2018), A suite of exercises for verifying dynamic earthquake rupture codes, *Seism. Res. Lett.* 89(3), 1146-1162, https://doi.org/10.1785/0220170222

Ramos, M.D., P.Thakur, Y. Huang, R.A. Harris, and K.J. Ryan (2022), Working with dynamic earthquake rupture models: A practical guide, S*eism. Res. Lett.*, 93(4): 2096–2110, https://doi.org/10.1785/0220220022

SCEC Dynamic Rupture Code Verification Project: https://strike.scec.org/cvws/

SCEC Simulations of Earthquakes and Aseismic Slip Project: https://strike.scec.org/cvws/seas/

SCEC Stress Drop Validation Project: https://www.scec.org/events/2025-scec-stress-drop-workshop/

Workshop Agenda

Session 1: Workshop Overview and Introductions

09:00-09:15 Introduction to the Workshop (**Ruth Harris**)

09:15-09:20 *Participant Introductions (All, Zoom chat)*

Session 2: Introduction to the Science and New Discoveries (Talk times include Q&A)

09:25-10:00 Coseismic fault friction: Recent lab observations and links to natural faults (**Monica Barbery**)

10:05-10:20 2025 SCEC rheology workshop and new fault slip results for minerology and fabric (**Alexis Ault**)

10:25-10:40 Lab results for stress drop and fault slip: near-field stress measurements (**Eric Burdette**)

10:45-11:00 *Lightning Talks - 100-second pre-recorded talks about new science (**Zhiwei Wang, Lav Joshi, Amy Lu, Srisharan Shreedharan, Baoning Wu, Gabrielle Hobson, Peng Zhai, Jeremy Wong**)*

11:05-11:20 Break

11:25-11:40 Lab results for fault healing and asperity partitioning (**Jun Young Song**)

11:45-12:00 Lab results for thermal pressurization on rough faults (**Yuval Tal**)

12:05-12:20 Fault pseudotachylytes: recent advances and open questions (**Eric Ferre**)

12:25-13:00 Break

13:05-13:20 Lab results for strain and conductivity due to fault formation in stepovers (**Sara Beth Cebry**)

13:25-13:40 Evolution of fault strength in granite under hydrothermal conditions (**Tamara Jeppson**)

13:45-14:00 Group Discussion

14:05-14:20 *Lightning Talks - 100-second pre-recorded talks about new science **(Di Deng, Zeyu Lu, Yuto Sasaki, Betsy Madden, Duo Li, Alice Gabriel, Julian Lozos)***

14:20-14:40 Break

Session 3: Updates from related groups

14:40-14:55 CRESCENT - 3D fully coupled earthquake and tsunami benchmarks (**Fabian Kutschera**)

15:00-15:07 SCEC SEAS Project (**Valère Lambert**)

15:12-15:19 SCEC Community Stress Drop Validation Study (**Rachel Abercrombie**)

Session 4:

15:24-16:00 *Group Discussion and planning our next steps (**All**)*

Workshop Participants and their Affiliations:

Brad Aagaard, USGS
Rachel Abercrombie, Boston U
Claudia Abril, LMU
Alejandro Aguilar, USU
Carlo Andrenacci, U "G. d'Annunzio"
Solene Antoine, Caltech
Emma Armstrong, USU
Zainab Asaad, IUSS/Pavia/Italy
Alexis Ault, USU
Annemarie Baltay, USGS
Michael Barall, USGS
Monica Barbery, Brown/U of Utah
Nick Beeler, USGS
Hasti Bordbar, TAMU
Brittany Botell, U Memphis
Guadalupe Bravo, UC Riverside
Eric Burdette, USGS
Awais Butt, NUST
Sara Beth Cebry, USGS
Xiaofeng Chen, OK State
Meritxell Colet, Columbia
Lilibeth Contreras, UNAM
Chiara Cornelio, INGV
*Di Deng, CUHK
Alex DiMonte, USU
Jarod Domenge, UNIMIB
Benchun Duan, TAMU
Brittany Erickson, U Oregon
Ayomiposi Falade, CERI
Caiyuan Fan, ENS Paris
Wei Feng, GFZ
Eric Ferre, NMSU
Alice Gabriel, UCSD
František Gallovič, Charles University
Leslie Garcia, USU
Aakash Gupta, UAF
Ruth Harris, USGS
Elizabeth Hearn, USGS
Evan Hirakawa, USGS
Gabrielle Hobson, UCSD
Martin Hronek, Charles U
Lorraine Hwang, UC Davis
Abdullah Imran, UT El Paso
SeongJu Jeong, OU
Tamara Jeppson, USGS
Junle Jiang, U Oklahoma
Lav Joshi, Charles University
Sajan K C, USC
L'ubica Valentová K., Charles U

David Kammer, ETH Zurich
Yuko Kase, GSJ
Folarin Kolawole, Columbia U
Fahrettin Kuran, IUSS Pavia
Fabian Kutschera, UCSD
Christos Kyriakopoulos, CERI
*Valère Lambert, Apple
SGT Lamont, LDEO
*Duo Li, Earth Science New Zealand
Mingqi Liu, TAMU
Yajing Liu, McGill U
Julian Lozos, CSUN
Amy Lu, McGill
Zeyu Lu, USTC
Karen Luttrell, LSU
Shuo Ma, SDSU
Betsy Madden, SJSU
Evan Marschall, UCSD Scripps
Christipher Menges, USGS
Priyanka Mishra, IITR
Francesco Mosconi, Sapienza University
Chukwuebuka Nweke, USC
Kim Olsen, SDSU
Edric Pauk, USC/SCEC
Kwabena Poku-Agyemang, USU
Pierre Romanet, Geoazur
Badie Rowshandel, CEA
Yuto Sasaki, University of Osaka
Arushi Saxena, UC Davis
Srisharan Shreedharan, USU
Jun Young Song, Cornell
Yuval Tal, BGU
Mohamed Talaat, Simpson Gumpertz & Heger Inc.
Zizhuang Tang, TAMU
Rachel Preca Trapani, LMU Munich
Dimitri Trifunac, Stanford
Em Vogel, U Michigan
Dilini Walakulu Arachchige, SIU
Binhao Wang, USC
Zhiwei Wang, CNRS
Kyle Withers, USGS
Jeremy Wong, UCSD
Baoning Wu, UCSD
Suli Yao, ENS Paris
Clara Yoon, USGS
Peng Zhai, UMich
Lin Zhang, CUP
Wenqiang Zhang, Stanford

*participants who sent pre-recorded talks but were not in attendance that day