II. Technical Report

Final Report

Submitted by Ruth Harris and Michael Barall
to the Southern California Earthquake Center

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Report for SCEC Award #19121

January 8, 2020 SCEC Workshop

Dynamic Rupture TAG – The 2019 Ingredients Workshop – Fault Friction
(SCEC Project 19121)

Co-Principal Investigators:

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Proposal Category: Integration and Theory
Three SCEC Research Priorities (among others): P4.a, P3.c, P3.f

The SCEC workshop "Dynamic Rupture TAG – The 2019 Ingredients Workshop – Fault Friction" was held January 8, 2020, at Kellogg West Conference Center on the campus of California State University, Pomona, in Pomona, California. A total of 53 people participated, including 27 in-person and 26 remote-access. Our workshop attendees included scientists from the U.S.A., Canada, China, France, Germany, Japan, Mexico, New Zealand, and Switzerland. Twenty of our workshop participants were either graduate students or postdocs. The workshop agenda and participant list are on the last page of this report.
Many thanks to Tran Huynh and her team for helping to make this workshop happen.

This workshop was the second of a series of four SCEC5 workshops designed to evaluate the importance of each of the four ingredients required for dynamic earthquake rupture simulations. The four ingredients are: initial stress conditions, fault geometry, rock properties, and fault friction (Figure 1). This workshop included a range of views of how fault friction operates in the Earth, based on information from lab experiments, from field observations, and from dynamic rupture simulations. The participants also learned about two current related SCEC projects: the dynamic rupture code validation project and the surface fault displacement project.

Ruth Harris (U.S. Geological Survey; USGS) welcomed the participants to the workshop. She then introduced and quickly summarized how dynamic rupture simulations work. She noted that at this time in our research endeavors, the SCEC-USGS Dynamic Rupture Code Verfication Group has done a commendable job checking that code results are reproducible for a variety of assumptions about the initial stresses, fault geometry, rock properties, and fault friction [e.g., as discussed in Harris et al., SRL, 2018]. This means that what is mostly needed is a basis for choosing among the multitude of possibilities for these ingredients. The November 2018 SCEC workshop focused on ingredient #1, fault geometry. This January 2020 SCEC workshop's focus was on ingredient #2, fault friction, perhaps a more challenging assignment than the previous one because fault friction is more difficult to observe or infer. Harris also asked the workshop participants to consider if there are any friction hypotheses that can be considered irrelevant, as a means of narrowing the field of fault-friction possibilities. (As mentioned later in this report, unfortunately, the answer was no.)

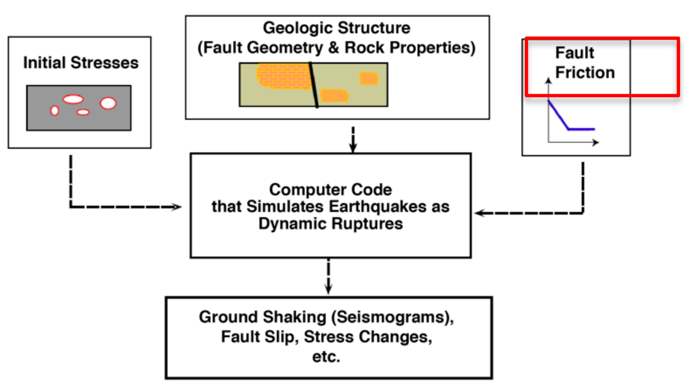

Figure 1. (Lightly modified Figure 1 from Harris et al., 2018). Components necessary for a spontaneous rupture simulation. Spontaneous earthquake rupture simulations need assumptions about the initial stresses on the fault (and off the fault also, if the medium is not elastic), the fault geometry, the off-fault materials, and a failure criterion, which describes how fault friction works. These physics-based computer simulations can be used to produce many different types of results, including patterns of fault slip, ground and sub-surface shaking, heat generation, etc. Please also see Harris [2004].

In the next talk of the morning, Fred Chester (Texas A & M University; TAMU) presented an overview of fault friction from theoretical considerations, field observations, and lab experiments. He first presented the evidence of seismic faulting in the rock record, and how the earthquake energy budget includes sizeable frictional work that leads to expected melting. However, he posited that this melting occurs only if the other likely coseismic weakening mechanisms, such as flash weakening, thermal pressurization, or other processes are insufficiently activated. Next, Chester talked about the adhesion theory of friction (Aharanov and Scholz, 2018), and showed how it is a basis for understanding rate-state friction and flash weakening. Chester then pointed to another of our dynamic rupture 'ingredients', fault geometry, and noted how there are important interactions between fault roughness, stress (yet another of our ingredients), and fault friction, and that we need to consider both microscopic and macroscopic processes to obtain a full picture.

Nir Badt (Brown University) presented his laboratory work on thermal pressurization. He noted that although thermal pressurization is expected to be an important mechanism, the expectation is based on theory rather than experimental or field evidence. This new work is the first to demonstrate thermal pressurization in the lab. Badt then showed the setup for his laboratory experiments on Frederick diabase, a low-permeability rock that also has low silica content, so there is no gel weakening to complicate the results. He presented results from dry experiments with velocity steps, then results from wet experiments with velocity steps, on both low-displacement faults and high-displacement faults. Badt compared the stress drops induced by thermal pressuration on low- and high-displacement faults. He showed that low-displacement faults had more rapid pressurization leading to higher stress drops of shorter duration, while high-displacement faults had a slower pressurization rate over a longer duration. He noted that the pore-space compressibility played an important role, and, perhaps most importantly, that dilatancy due to fault roughness could eliminate thermal pressurization as a weakening mechanism. This is another case where the effects of the fault geometry ingredient interact with those of fault friction.

Next, Tamara Jeppson (USGS) presented an overview of international fault drilling experiments that are used to collect information about physical properties of active fault zones, including the classic example of SAFOD, on the San Andreas fault. Jeppson highlighted the advantages of these types of data collection in that the faults are known to be currently seismogenic, in contrast to more-commonly studied exhumed faults that are inferred to have been active in the past, and whose geological trip from depth to the Earth's surface over millions of years may contaminate the observations. She emphasized to the audience the physical and financial challenges of collecting deep drilling data, and mentioned that these deep drilling ventures are international collaborations funded by international funding organizations. Recent drilling experiments include SAFOD on the San Andreas fault, JFAST (the Japan Trench Fast Drilling Project) that drilled the toe of the Japan Trench accretionary prism near the 2011 Tohoku earthquake, and drilling experiments in the vicinity of the 1999 Chi-Chi and 2008 Wenchuan earthquakes. Most, if not all, of these drilling expeditions find low values for the apparent coefficient of friction. Goals in the future, some of which involve overcoming major technological obstacles, include drilling to deeper depths across active fault zones, and longterm borehole monitoring.

The next two talks following the break were by Noah Phillips (McGill University, Canada) and David Lockner (USGS). Phillips asked the question of what the strength is of pseudotachylite during the different parts (coseismic, postseismic, interseismic) of the seismic cycle, then he delved into the geology and geochemistry to explain the presence (and sometimes lack thereof) of this frictional melt feature. He presented laboratory evidence that shows pseudotachylite to be coseismically weak, yet postseismically strong (i.e., stronger than the sliding strength) thereby leading to new fault surfaces. This seems to indicate that pseudotachylites should be ubiquitous in the field. He then showed how pseudotachylites are unlikely to survive throughout the geologic record, and how other mineral assemblages may substitute for them in some settings. He noted that although pseudotachylites are easy to spot in a light-colored rock matrix, a dark-colored rock matrix may hide their presence. He concluded with the idea that frictional melts do often occur, however their evidence is not always easy to find and that pseudotachylites will primarily occur in dry fault-zone settings.

David Lockner showed new results from the USGS rock mechanics lab investigating the effects of undrained pore-pressure on faulting. One of the goals of the work was to determine if the study by Segall and Rice (1995), a 1D rate-state friction model of a fully drained system that assumed porosity change dependent only on velocity, was viable. Lockner's experiments involved direct measurement of pore-pressure effects with one set of experiments including a layer of quartz gouge, and the second set a bare surface. The experiments with gouge showed a dilatant expansion of the fault zone, with an accompanying decrease in pore-pressure, and subsequent recovery as the amount of slip increased. With larger velocity kicks, stable weakening occurred similar to slow slip events, and with even harder velocity kicks, the system produced an instability, that was driven by pore-pressure collapse. He noted that this was not a study involving thermal pressurization, instead it was of the stability or instability of the gouge zone, with pore-pressure effects, and that the results depend on the speed that the system is kicked (i.e., this is not a steady state process). The bare surface experiments showed a similar sensitivity to the pore-pressure changes, which are different from either the drained case or dry rate-state friction (a-b) effects. Lockner concluded that the Segall and Rice (1995) paper is indeed still relevant.

In the afternoon, Valere Lambert (Caltech) transitioned the participants to thinking about computational simulations, energy balance, crack versus pulse models, and the temperature effect in shear heating models. He presented the idea of two end-member models that could explain the apparent lack of heat production in mature faults: one where faults are persistently weak and one where faults are dynamically weak (i.e., are strong until sliding starts and then rapidly weaken). He showed how one might have reasonable stress drops and remain primarily in a low stress regime, even with mild thermal pressurization. He also noted that strong enhanced weakening with thermal pressurization greatly lowers the average stress level so that one no longer has seismicity at all, perhaps an explanation for regions where there is a scarcity of microseismicity.

Hongfeng Yang (Chinese University of Hong Kong) presented his work on searching for the appropriate parameters to use for slip-weakening friction. He gave examples from the 2015 Gorkha, Nepal earthquake and the 2012 Nicoya Peninsula earthquake, and showed how one could use the seismological data to infer the slip-weakening parameters and stress drop values.

Next, we had two presentations about current SCEC projects with applications that are quite relevant to our group. Kyle Withers (USGS) presented the latest news about the SCEC dynamic rupture code validation project, whereby a number of dynamic rupture modelers are simulating earthquakes on a vertical strike-slip fault set in a fixed 1D velocity structure, but with most other parameters free to vary. Each modeler creates a set of model results (known as realizations) by introducing stochastic variability into the model, for example by including a stochastically-generated pattern of initial stress. The goal is to explore whether the range of ground motions produced by these simulations is comparable to the range observed in real earthquakes.

Christine Goulet (Southern California Earthquake Center) described and discussed the fast-paced one-year surface fault displacement project which is a joint effort with UCLA. She mentioned that the project is compiling a database and also using computational simulations, with the goal to update the empirical relations for surface displacement in Wells and Coppersmith [1994].

In the final session of the day, there were three talks about dynamic rupture simulations and fault friction implications. Eric Dunham (Stanford University) started the session with a comprehensive overview of friction ideas that are commonly used. He emphasized that the most appropriate form of friction (and other ingredients) to use is the formulation that is most appropriate for the science problem that we are trying to solve. Dunham showed how slip-weakening could be sufficient for single event simulations, but that one does often need to add a stochastic element, in stress or geometry. He showed that as our science evolves from purely coseismic simulations to full earthquake-cycle simulations that include inertia, there is a need to adopt rate-state friction formulations, because they account for transient slip and fault healing. Full cycle simulations are an advantage in that they provide the initial stress conditions for the next earthquakes that occur. Dunham concluded by asking the question of how much emphasis do we want to place on the fine details of friction behavior when we still have outstanding questions about our other ingredients, including plastic yielding, fluids and stress.

Ben Duan (TAMU) showed how the choice of friction parameters affects the likelihood of earthquake rupture past large geometrical fault complexities (i.e., 'earthquake gates') and that this is particularly an issue in low-stress settings. He showed how to equate slip-weakening parameters with rate-state parameters, then presented examples of simulations that he and his group have done for earthquakes on the Altyn Tagh fault, and for the case of a geometrical asperity on a fault surface.

For the final talk of the day, Alice Gabriel (Ludwig Maximilians University, Germany) showed some of her group's computational simulations of large earthquakes, including the 1992 Landers earthquake, the 2004 Sumatra earthquake, the 2016 Kaikoura earthquake, and the 2019 Ridgecrest earthquakes. She noted that her group's simulations use strongly rate-weakening friction, are loaded from the bottom of the fault zone, and also, when possible, account for independent information available about the regional stress orientations before the large earthquake. The simulations are able to match the observed seismic and geodetic data. Gabriel finished her talk by showing the design of a new benchmark for dynamic rupture modelers to implement, thermal pressurization in three-dimensions. In the past, our dynamic rupture group had conducted a comparison of results using thermal pressurization in two-dimensions (TPV105-2D, see scecdata.usc.edu/cvws), but Gabriel pointed out that this new 3D exercise has better parameters, and we will tackle it as a group dynamic rupture exercise later in 2020.

The workshop participants had a rewarding day of talks and discussions about fault friction and learned about the myriad of ideas about how fault friction might work. At the end of the day no coseismic friction hypotheses had been deemed to be irrelevant, except that it was noted that slip-weakening is likely inadequate for full-eartquake-cycle modeling. An important point that was agreed upon by many is that the appropriate choices for this ingredient should depend on the application and the study setting.

For the workshop agenda and some of the presentation pdf's, please also see the SCEC workshop website: https://www.scec.org/workshops/2020/dynrup

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Some References:

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Wells, D.L., and K.J. Coppersmith (1994), New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seism. Soc. Am., 84(4), 974–1002.

SCEC Dynamic Rupture Group Ingredients Workshop on Fault Friction
Conveners: Ruth Harris and Michael Barall
SCEC Award and Report: 19121
Location: Kellogg West Conference Center, Pomona, CA
Date: January 8, 2020

08:30 - 09:00	Workshop Check-In	
09:00 - 09:20	Welcome, Overview of Workshop Objectives, and Participant Introductions	Ruth Harris (USGS)
	Session 1: Views of Coseismic Friction, from the Lab and the Field	
09:20 - 09:45	Overview: Friction in the lab and field	Fred Chester (TAMU)
09:45 - 10:05	Thermal pressurization in laboratory experiments	Nir Badt (Brown)
10:05 - 10:25	Insights from deep drilling - case studies	Tamara Jeppson (USGS)
10:25 - 10:45	Discussion	*All*
10:45 - 11:00	Break	
11:00 - 11:20	The frictional strength of fault rocks before, during, and following earthquakes: Insights from the field and experiments	Noah Phillips (McGill)
11:20 - 11:40	Recent lab observations concerning stability of hydraulically isolated faults	David Lockner (USGS)
11:40 - 12:00	Discussion	
12:00 - 13:00	*Lunch*	
	Session 2: Views of Coseismic Friction, from the Lab, Field, and Modeling	
13:10 - 13:30	Constraining physical conditions for the low-stress, low-heat operation of mature faults	Valere Lambert (Caltech)
13:30 - 13:50	Probing frictional properties on seismogenic faults with constraints from near-field data	Hongfeng Yang (CUHK)
13:50 - 14:15	Update - Dynamic Rupture Code Validation Project	Kyle Withers (USGS)
	Update - Surface Rupture Project	Christine Goulet (SCEC)
14:15 - 15:10	Discussion	*All*
15:10 - 15:30	*Break*	
	Session 3: Dynamic Rupture Simulations and Friction - Current Practice	
15:30 - 15:55	Overview: Friction used in Dynamic Rupture Computational Simulations	Eric Dunham (Stanford)
15:55 - 16:15	Friction law and level matter in dynamic ruptures of earthquake gates	Ben Duan (TAMU)
16:15 -16:35	Dynamic rupture simulations of recent earthquakes	Alice Gabriel (LMU)
16:35 - 17:30	*Discussion*	All
17:30	Adjourn	

PARTICIPANTS: (*=Remote Participants)

*Brad Aagaard (USGS)	*Dmitry Garagash (Dalhousie)	*Shuo Ma (SDSU)
Kali Allison (U Maryland)	Christine Goulet (USC)	David Oglesby (UCR)
*Pablo Ampuero (Caltech)	Ruth Harris (USGS)	*Kim Olsen (SDSU)
Khurram Aslam (U Oregon)	*Jorge Hayek (LMU)	Edric Pauk (USC)
*Nir Badt (Brown)	*Sebastien Hok (IRSN)	*Andrea Perez (Victoria)
*Michael Barall (Inv. Software)	*Yihe Huang (Michigan)	Noah Phillips (McGill)
Nick Beeler (USGS)	Tran Huynh (USC)	Arben Pitarka (LLNL)
*Lucile Bruhat (ENS)	Tamara Jeppson (USGS)	*Sohom Ray (Dalhousie)
Fred Chester (TAMU)	Junle Jiang (Cornell)	*Kanya Sudhir (Caltech)
Jordan Cortez (UCR)	*Yoshi Kaneko (GNS)	Prithvi Thakur (Michigan)
Luis Dalguer (3Q-Lab)	*Yuko Kase (AIST, GSJ)	Terry Tullis (Brown)
Ben Duan (TAMU)	*Taeho Kim (Caltech)	Yongfei Wang (USC)
*Eric Dunham (Stanford)	Valere Lambert (Caltech)	*Kyle Withers (USGS)
*Kenneth Duru (ANU)	Nadia Lapusta (Caltech)	Baoning Wu (UCR)
Ahmed Elbanna (UIUC)	*Duo Li (LMU)	*Hongfeng Yang (CUHK)
Brittany Erickson (Oregon)	Dunyu Liu (TAMU)	*Suli Yao (CUHK)
Alice Gabriel (LMU)	David Lockner (USGS)	*Zhenguo Zhang (SUSTech)
*Percy Galvez (ETHZ)	Julian Lozos (CSUN)	