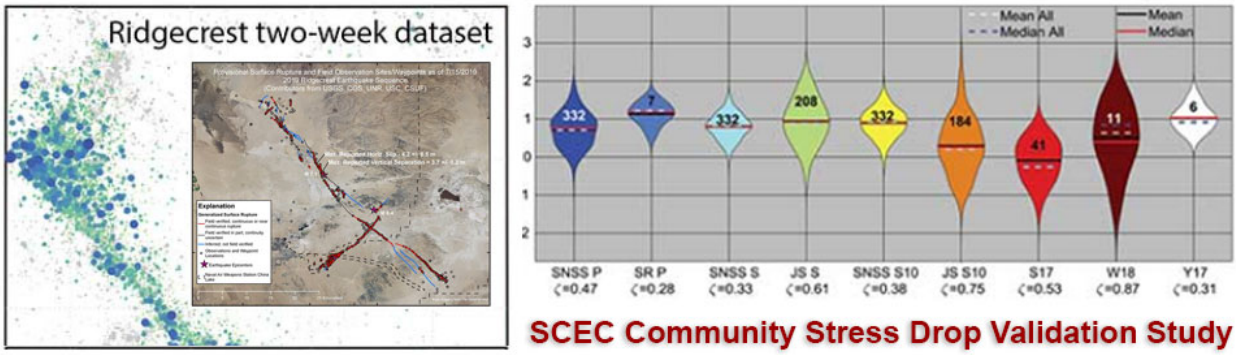

Final Report for SCEC Award 21114:
Community Stress Drop Validation Workshop
Under the Technical Activity Group for the Community Stress Drop Validation Study

Submitted by Annemarie Baltay
and Rachel Abercrombie

November 4, 2021 SCEC Workshop
"Stress Drop Validation – Planning and Preliminary Results"

SCEC Award: 21114
Amount Requested: $0
Category: Workshop Proposal
Conveners: Annemarie Baltay (USGS) and Rachel Abercrombie (Boston University)

SUMMARY of TAG: The motivation for the SCEC Technical Activity Group (TAG) for Community Stress Drop Validation Study is focused on understanding the nature and causes of discrepancies in earthquake stress drop, as well as where random and physical variability arises. We observe differences in stress drop estimates from different researchers, even when applying the same underlying method. We also observe differences between methods and data selections, even when applied by the same researcher. These differences are often larger than the calculated uncertainties, making it hard and confusing to use these measurements for ground motion prediction and to study earthquake source physics.

In this context, the main goals for the TAG are to use a common data set of records from the 2019 Ridgecrest earthquake sequence (consisting of over 12,000 events of M1 to M7.1) to address the questions:

- How do differing methods and model assumptions affect stress drop estimates? How do different researchers approach similar methods?
- How do data quantity, quality, selection and processing affect stress drop estimates?
- How do physical source (mechanism, depth, radiation pattern, directivity), path (geometrical spreading, attenuation), and site (soil conditions, site attenuation) features affect the estimates?
- What measurements, and uncertainties, would be most useful for the broader community?

WORKSHOP 1 OVERVIEW. Workshop #1 "Stress Drop Validation – Planning and Preliminary Results" was held as a Zoom meeting on November 4, 2021. Anyone currently working on, or interested in, the science questions noted above and/or learning about Ridgecrest earthquake studies was encouraged to apply to participate, especially researchers and young investigators. We received 132 registrations, and 101 participants from 14 countries on 5 continents (Appendix B). We asked each registrant to fill out a survey indicating their interest in stress drop, what they hoped to get out of the workshop, if they planned to use the common data set to estimate stress drop, if they intended to submit a SCEC proposal under the TAG, and other demographic information. We solicited preliminary results estimating stress drop using the common dataset, and used those results in the workshop to start discussion (more details on those actual results below). As one overarching goal for the workshop was simply to facilitate communication between different research groups and disciplines, and to build (and maintain) project momentum, we experimented with formats in different sessions, built in lots of time for discussion and breakout rooms, and had fewer long talks. We also worked to ensure a diverse group of speakers and moderators, prioritizing early-career researchers and gender equity. The decision to include both observational seismologists making measurements, and users of those measurements was clearly successful with both groups contributing and learning from one another. The workshop also proved beneficial to the many students who participated, looking to understand the problems and meet the community as they begin work in this field

PRELIMINARY RESULTS: The common dataset was made available on the website in late spring 2021, and prior to the workshop, all were invited to analyze the data and provide estimates of stress drop, corner frequency, or other similar source parameters. Approximately one month prior to the workshop, the registration email survey asked participants if they would be supplying stress drop estimates. We then followed up with those who indicated "yes" or "maybe" and provided a template Excel worksheet in which to submit their results. We requested the results be returned about 10 days prior to the workshop, on October 25, 2021.

We received submissions of initial results from 11 research groups (14 submissions when counting that some researchers submitted two methods), many more than we expected! Between October 25 and November 4, PIs Abercrombie and Baltay made some initial comparisons and analysis of the results. Direct comparison of the reported stress drops reveals considerable scatter, which was not surprising, but perhaps some stronger correlation between results using similar methods (**Figure 1**).

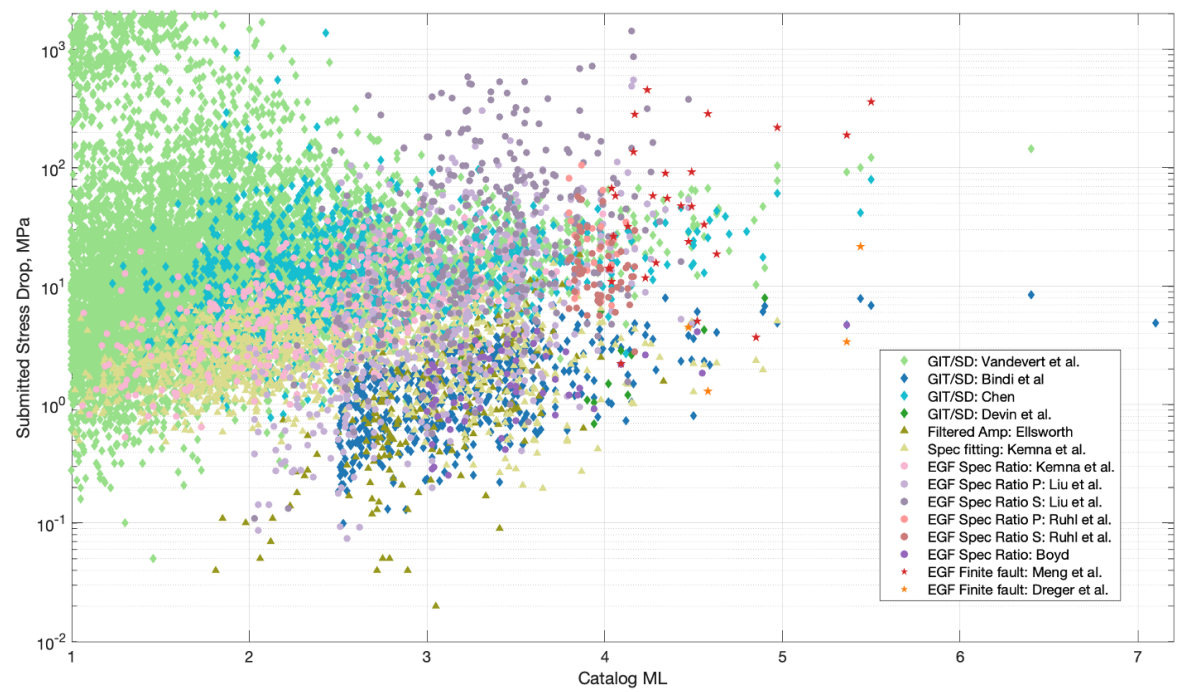

Figure 1. Initial submitted stress drop results from 11 research groups (legend), vs catalog magnitude. Generalized Inversion Technique (GIT)/ Spectral Decomposition (SD) methods are shown with diamond symbols; empirical Green's function (eGf) spectral ratio methods shown in dots; eGf finite fault in stars; and other methods in triangles.

A main goal of this initial analysis was to guide the TAG on how to proceed over the next year. One idea was to identify some events to focus on, to narrow the scope from the 12,000+ events in the common data set. To that end, we identified a set of 22 events for which stress drop was estimated by 8 or more out the 14 submitted initial results (**Figure 2**). Here we can see that there are some events that have less variability between estimates (e.g., the smallest magnitude event) while others have larger variation between methods.

WORKSHOP PROCEEDINGS. The Workshop was divided into three Sessions, each with a specific focus, and a different logistical format (Agenda in Appendix A).

In Session 1, we started the workshop with a welcome from Annemarie Baltay, and a quick data overview from Taka'aki Taira. Rachel Abercrombie then gave an overview of the TAG's goals in light of recent published work and framing the problem. Each of the research groups who submitted initial results then presented three slides (as part of a shared Google Slides deck) briefly describing their methods. We divided the methods generally into four different types: (1) Spectral Decomposition / Generalized Inversion - *Inverting a set of spectra simultaneously for source, site, and path effects, then model fitting source spectra*; (2) Spectral

Ratios/eGf frequency domain - *Co-located eGf event used to isolate source from path and site effects, then model fitting source spectra: frequency domain*; (3) Source time functions/eGf time domain - *Co-located eGf event used to isolate source from path and site effects, then model fitting source time functions: time domain*; and, (4) Other – Arias intensity; filtered amplitudes, single station. Rachel Abercrombie then showed some preliminary comparisons of the submitted preliminary results, and we started discussion before the break.

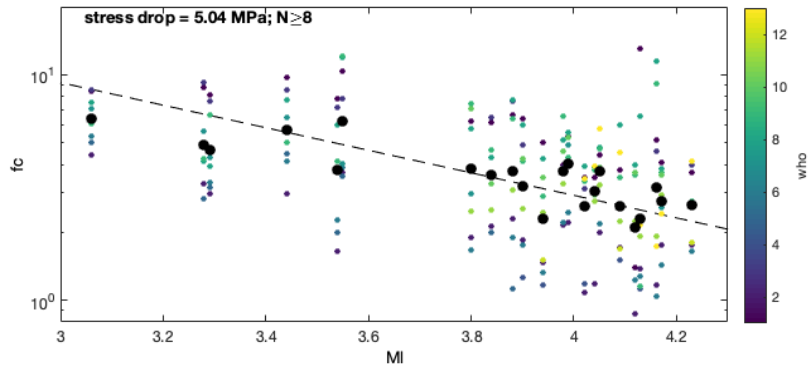

Figure 2. Initial submitted results for 22 events which were analyzed by 8 or more (out of 14) methods, plotted as estimated corner frequency vs catalog magnitude. Solid black dots are the $\log_{10}$ averaged across all methods; colors show the different estimates. Some events (smallest ML) show relatively less variability as compared to some of the larger events.

Session 2 kicked off with a keynote talk by Colin Pennington (early-career) entitled *Comparisons of Stress Drop Results: a Focus on the Prague, OK Sequence*. Colin discussed his work performing a stress drop validation study with the Prague sequence, in which he used several different methods to estimate stress drop in comparison with some published studies. This talk got the group thinking about how to proceed forward in our TAG study. We then broke into three consecutive sets of breakout rooms. The first was two large rooms each focused on one of the two main methods: Spectral decomposition (led by Natalie Schaal), and spectral ratios (led by Oliver Boyd). The second set of rooms had 12 rooms with a moderator each, to discuss "What can we measure reliably, and to what extent?". Participants then mixed up and again had 12 rooms, discussing the question "As a community, what should we focus on for the validation study?". During each of these breakout rooms, moderators and breakout room leaders added notes and comments to a shared Google Doc that Baltay and Abercrombie will refer to for future planning. We then returned to the large group and rather than having a strict report-out of the rooms, kept the discussion going on what we can and should measure and what we should focus on over the next year. Key themes that arose during this session and continued to be honed in session 3 included: identification of other parameters and information needed to be provided during results submission; identification of a subset of events for focused study; collaboration between different groups using similar approaches to identify the more critical analysis choices; potential for a related simulation study using synthetically generated records (so we know the "real" stress drop); and, more frequent informal virtual discussion meetings to coordinate progress.

Session 3 was moderated by Christine Goulet and Ahmed Elbanna and focused jointly on the needs and priorities of "users" of stress drop estimates, and looking forward to the next year of the TAG. We had four short presentations of 5 minutes each on the topics of Stress Drop in Ground Motion presented by Behzad Hassani; Static Stress Drop for Scaling Relations in Seismic Hazard by Bruce Shaw; Stress Drop in Dynamic Rupture Simulations by Ruth Harris; and Stress Drop in Source Physics by Valere Lambert. These talks really got participants excited about the different applications of stress drop and there were great questions. We then opened up four breakout rooms, each with one of the four presenters and a moderator (Christine Goulet,

Andy Michael, Baoning Wu and Ahmed Elbanna), and participant chose which to join for continued, deeper discussion. Again, moderators noted big ideas into the shared Google Doc. Discussions in those rooms surrounded the preceding lightning talks, but also future directions for the TAG. We then regrouped in the main room and continued developing ideas for the next year of the TAG, which included the idea of ~monthly Zoom meetups, perhaps with sub-groups (same methods or uses).

DISCUSSION TOPICS: Throughout the workshop there were lots of great discussions about certain methods or approaches that we can expand on in future meetings and workshops. Consistent comments focused on:

- Focus on magnitude range, etc that we are confident in. We should choose a subset of events to all focus on.
- What frequencies are being fit? In general, more information needs to be reported.
- What can we say about events that "failed" a method?
- Consistency of terminology (e.g., eGf vs. constraint function or empirical correction spectrum).
- How to best report uncertainties? There are many sources of uncertainty: model selection, inversion, data, different records, different eGf, different assumptions, etc. And there is real variability in earthquake recordings.
- It seems that the most consistent results are for events in the 3-7km range. How can we address any depth dependencies in the methods?
- There is considerable discrepancies in the moment and magnitude estimates. Additionally, how are people defining sheer modulus, radiation pattern, etc? This should be a future focus.
- Tradeoffs – between corner frequency and moment, source and path effects
- Should we also compare our site and path corrections?
- What are the assumptions between methods that estimate corner frequency as opposed to those that go directly to stress drop? What about the difference between Brune and Madariaga stress drops?
- Effect of different eGfs or reference/constraint events.
- Can we use synthetically (dynamic rupture) generated earthquake-station records to use in the analysis, with known stress drops?
- Improve link between estimated stress drops here and those used in dynamic rupture simulations, etc.
- Can consistent QC/QA help?
- Source complexity that is not fit by the Brune model – how is that treated in different methods? We perhaps expect agreement between methods for events that are "simple" (aka more Brune-like?).

FUTURE TAG DIRECTIONS. One main goal of the workshop was to decide as a community what the next steps should be. The group decided on several main thrusts going forward, generally divided into scientific pursuits and organizational ones.

Scientific directions:

- Continued analysis of stress drop. Many researchers submitted very preliminary results, so they will refine their results based on feedback from the workshop. Others were not able to submit results in time for Workshop #2, so they will continue to work

towards submitted results for Workshop #2. Many researchers became aware of others using similar and different methods, and have already reached out to start collaborations with one another.

- Determine a subset of ~50 events for all groups to focus on. These events will include the 22 already identified (of M3 – 4ish that were already analyzed by 8 or more methods) and augment with some larger and smaller events and ensure an even distribution of hypocentral depths, recording stations, etc. Participating groups that only analyze a smaller number of events would then be encouraged to prioritize these to ease comparisons.
- Consider generating synthetic earthquake records, with known stress drop, to use in the inversions.

Organizational directions:

- Two workshops next year in 2022 – one virtual to include more people, and hopefully one in person, preferably associated with the Annual Meeting.
- Monthly-ish Zoom meetups, perhaps by topic – methods, user needs, data processing. To start in January.
- SCEC proposals due Nov 23, let PIs Baltay and Abercrombie know if you are planning to submit under the TAG.

FEEDBACK FROM PARTICIPANTS. Following the workshop, we followed up with all the presenters and moderators for their feedback about the format and content of the workshop. As we had experimented with a variety of different talk and discussion formats, we were curious to see what had worked best. People were unanimously happy and excited about the workshop and felt they learned a lot and connected with many colleagues, new and old. Everyone enjoyed the lengthy discussion times and breakout rooms. Only one criticism came through, that the smaller breakout rooms (#2 and #3) had too few people in each, so that discussion was awkward in some. These rooms had fewer participants than we had initially intended, but last-minute small technical problems prevented us from adjusting. Next time we will keep all the discussion time but learn from the logistical/technical limitations, and also ensure breakout rooms have more participants.

APPENDIX A: WORKSHOP AGENDA

09:00 - 10:30	**Session 1: Introductions and Comparisons of Initial Results** *Moderators: Rachel Abercrombie, Annemarie Baltay*	
09:00 - 09:20	Welcome and Overview of Workshop, Datasets	Rachel Abercrombie, Annemarie Baltay, Taka'aki Taira
09:20 - 09:50	Lightning Talks: Methods by Different Research Groups who submitted preliminary results	*11 Groups*
09:50 - 10:00	Initial Results	Rachel Abercrombie
10:00 - 10:30	Group Discussion	*All*
10:30 - 11:00	*Break*	
11:00 - 12:30	**Session 2: Method Comparisons—Breakouts and Discussion** *Moderators: Oliver Boyd, Natalie Schaal*	
11:00 - 11:15	Comparisons of Stress Drop Results: a Focus on the Prague, OK Sequence	Colin Pennington

11:15 - 11:35	Breakout Discussion #1: Initial results by methods • Participants self-select the breakout room • Room A: EGF • Room B: GIT/spectral decomposition	*All*
11:35 - 11:55	Breakout Discussion #2: What can we measure reliably, and to what extent? Participants self-select the breakout room, each breakout has assigned moderator noted in parentheses below • Room A (Oliver Boyd) • Room B (Natalie Schaal) • Room C (Xiaowei Chen) • Room D (Yihe Huang) • Room E (Clara Yoon) • Room F (Sue Hough) • Room G (Bill Ellsworth) • Room H (Wenyuan Fan) • Room I (German Prieto) • Room J (Thomas Goebel) • Room K (Christine Ruhl) • Room L (Colin Pennington)	*All*
11:55 - 12:15	Breakout Discussion #3: As a community, what should we focus on for the validation study? • Participants self-select the breakout room (A-L), each breakout has assigned moderator (same Breakout Discussion #2)	*All*
12:15 - 12:30	Group Discussion	*All*
12:30 - 13:30	*Break*	
13:30 - 15:00	**Session 3: User needs lightning talks and looking forward** *Moderators: Ahmed Elbanna, Christine Goulet*	
13:30 - 13:40	Introduction	Rachel Abercrombie, Annemarie Baltay
13:40 - 13:45	Stress Drop in Ground Motion	Behzad Hassani
13:45 - 13:50	Static Stress Drop for Scaling Relations in Seismic Hazard	Bruce Shaw
13:50 - 13:55	Stress Drop in Dynamic Rupture Simulations	Ruth Harris
13:55 - 14:00	Stress Drop in Source Physics	Valère Lambert
14:00 - 14:20	Breakout Discussion #4: User needs for stress drop Participants self-select the breakout room, each breakout has assigned moderators noted in parentheses below • Room A (Behzad Hassani, Christine Goulet) • Room B (Bruce Shaw, Andrew Michael) • Room C (Ruth Harris, Baoning Wu) • Room D (Valère Lambert, Ahmed Elbanna)	*All*
14:30 - 15:00	Group Discussion: Looking Forward	*All*
15:00	*Adjourn*	

APPENDIX B: WORKSHOP PARTICIPANTS (101 total)

Rachel Abercrombie (Boston Univ)
Pablo Ampuero (Geoazur, IRD/UCA)
Pablo Aravena (Saint Louis Univ)
Ralph Archuleta (UCSB)
Marcelo Assumpção (Univ São Paulo)
Annemarie Baltay (USGS)
Michael Barall (USGS)
Yehuda Ben-Zion (SCEC/USC)
Allison Bent (Natural Res Canada)
Susan Bilek (New Mexico Tech)
Dino Bindi (GFZ Potsdam)
Aglaja Blanke (GFZ Potsdam)
Carolyn Boulton (Victoria Univ)
Oliver Boyd (USGS)
Giovanna Calderoni (INGV)

Hilary Chang (MIT)
Xiang Chen (Chinese Univ of HK)
Xiaowei Chen (Univ of Oklahoma)
Shanna Chu (Brown)
Elizabeth Cochran (USGS)
Leonardo Colavitti (INGV)
Emma Devin (USGS)
Douglas Dreger (UC Berkeley)
Ahmed Elbanna (UIUC)
Bill Ellsworth (Stanford)
Wenyuan Fan (SIO/UCSD)
Abhijit Ghosh (UC Riverside)
Thomas Goebel (Memphis, CERI)
Christine Goulet (SCEC/USC)
Tom Hanks (USGS)
Jeanne Hardebeck (USGS)
Rebecca Harrington (Ruhr Univ)
Ruth Harris (USGS)
Behzad Hassani (BC Hydro)
Egill Hauksson (Caltech)
Joanna Holmgren (Univ of Bristol)
Susan Hough (USGS)
Yihe Huang (UMich)
Tran Huynh (USC/SCEC)
Nadine Igonin (UT Austin)
Chen JI (UCSB)
Junle Jiang (Univ of Oklahoma)
Kilian Kemna (Ruhr Univ Bochum)
Debi Kilb (SIO/UCSD)
Trey Knudson (Stanford)
Christos Kyriakopoulos (U Memphis)
Valere Lambert (UCSB)
Nadia Lapusta (Caltech)
Bo Li (LMU)
Guoqing Lin (Univ of Miami)
Meichen Liu (UMich)
Julian Lozos (CSUN)
Kuo-Fong Ma (Academia Sinica)
Jose Magana (UC Berkeley)
Luca Malagnini (INGV)
David Marsan (ISTerre)
Kevin Mayeda (AFTAC)
Andrew Michael (USGS)
Paola Morasca (INGV)
Jim Mori (Kyoto Univ)
Francesco Mosconi (Univ Sapienza)
Pamela Moyer (New Hampshire)
Irene Munafò (INGV)
James Neely (Northwestern)
Arjun Neupane (Univ of Tulsa)
Chukwuebuka Nweke (USC)
David Oglesby (UC Riverside)
Kristina Okamoto (UCSC)
Joses Omojola (LSU)
Roberto Ortega (CICESE)
Adrien Oth (ECGS)
Grace Parker (USGS)
Edric Pauk (USC/SCEC)
Colin Pennington (USGS)
German Prieto (Uni Nac Colombia)
Christine Ruhl (Univ of Tulsa)
Natalie Schaal (CSUN)
Sara Sgobba (INGV)
Bruce Shaw (Columbia)
David Shelly (USGS)
Shuzhong Sheng (E China Univ Tech)
Will Steinhardt (UCSB)
Mariano Supino (ERI)
Michelle Sutherland (Group Delta)
Taka'aki Taira (UC Berkeley)
Elisa Tinti (Università La Sapienza)
Sagar Tripathy (Tata Projects Ltd)
Daniel Trugman (UT Austin)
Ayako Tsuchiyama (MIT)
Takahiko Uchide (GSJ, AIST)
Ian Vandevert (UCSD)
Frank Vernon (UCSD)
Sebastian von Specht (Acad Sinica)
Yongfei Wang (SCEC/USC)
Katherine Whidden (Univ of Utah)
Baoning Wu (UC Riverside)
Changjiang Wu (Nuc Reg Auth, Japan)
Qimin Wu (Lettis)
Alan Yong (USGS)
Clara Yoon (USGS)
Keisuke Yoshida (Tohoku Univ)