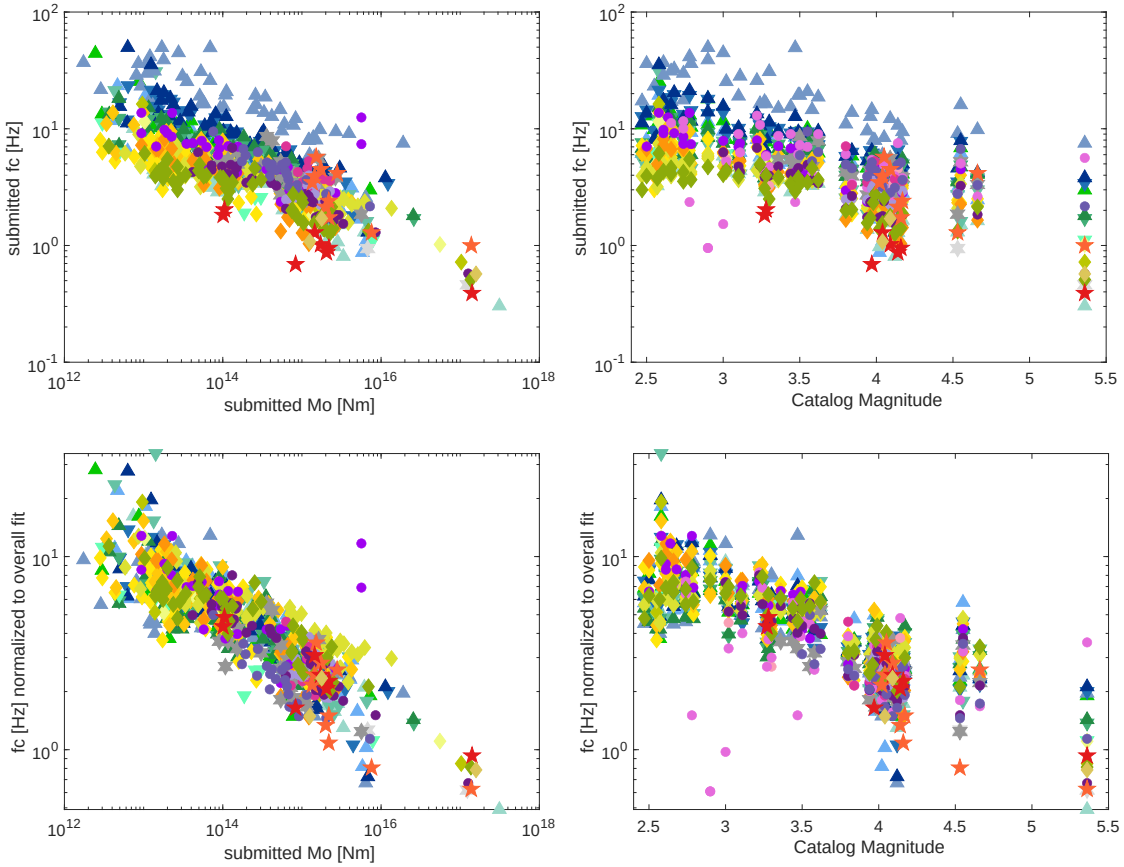
2022 Final Workshop Report for:
SCEC Award 22101: Two 2022 Workshops for the Community Stress Drop Validation Study TAG
using the 2019 Ridgecrest Earthquake Dataset

Workshop #2: September 10, 2022 in-person workshop
at the SCEC Annual Meeting, Palm Springs

Workshop #3: January 26, 2023 Virtual Zoom workshop
https://www.scec.org/workshops/2023/stress-drop



Submitted by Annemarie Baltay
and Rachel Abercrombie

SCEC Award: 22101
Amount Requested: $12,500
Category: Workshop Proposal
Conveners: Annemarie Baltay (USGS) and Rachel Abercrombie (Boston University)

SUMMARY of TAG: The motivation for this TAG is focused on understanding the nature and causes of discrepancies in earthquake stress drop, as well as where random and physical variability arises. In this context, the main goals for the TAG are to use a common data set of records from the 2019 Ridgecrest earthquake sequence 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, path, and site features affect the estimates?
- What measurements, and uncertainties, would be most useful for the broader community?

The TAG itself has three main tasks: (1) Coordination of the TAG, which includes workshop organization, hosting monthly Zoom meetups, distribution of datasets, and designing and coordinating benchmarks; (2) Analysis of Ridgecrest stress drops by individual PIs; and, (3) Meta-analysis of the individual stress drops, to understand the sources of variability. Since the start of the TAG in 2021, co-PIs Abercrombie and Baltay have gathered the global community through a website, mailing list, monthly Zoom calls (begun in March 2022, 8 to date), conference sessions and meet-ups, and two successful workshops. TAG co-PI Taira generated, distributed, and trouble-shot a common waveform database based on a two-week subset of M >1 and larger earthquakes which occurred in the Ridgecrest vicinity, and a subset of 55 events. To date, we have received full results for a total of 21 unique submissions (Figure 1). Abercrombie, Baltay and Chu have been performing meta-analysis to guide the group comparisons.

The TAG held its first Workshop #1 on November 4, 2021 virtually on Zoom with 101 participants. Covered in this report are Workshop #2 held in-person on September 10, 2022 at the SCEC Annual Meeting and Workshop #2 held virtually on Zoom on January 26, 2023.

WORKSHOP 2 OVERVIEW. The September 2022 Stress Drop Validation TAG workshop was held in person at the Hilton Palm Springs on Saturday September 10, prior to the SCEC Annual Meeting. The aim of the TAG is to improve awareness and understanding of the nature and causes of discrepancies in earthquake stress drop estimates, as well as where variability arises. We observe differences in stress drop estimates from different researchers, even when applying similar methods, and 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.

The September workshop was relatively focused, with the aim of engaging those who make stress drop measurements in detailed discussion and comparison of the submitted results from the various methods (see Appendix A for the workshop agenda). The format of the workshop was designed to prioritize discussion and interaction between participants. 24 people attended in person, with an additional 6 active on Zoom (see Appendix B for list of participants). Prior to the workshop, we received many submitted results of estimated stress drop, for a total of 21 submissions by various research groups, 5 of which were led by students (one undergrad) and 4 were from groups outside of the US.

Earlier in 2022, 55 events were selected for focus, and researchers were asked to include those events in their studies. In the week prior to the workshop, we held a pre-meeting Zoom at which we identified 6 events to discuss in detail at the in-person workshop. Abercrombie, Baltay and Chu presented initial meta-analysis of the individual results, with a focus on the 55 selected events that most researchers studied, and detailed comparison of the 6 events. Direct comparison

of the reported stress drops reveals considerable scatter, which was not surprising, and significant scatter in estimated seismic moments, as well. Each of the teams who submitted results was then invited to present a very short lightning overview of their methods. Researchers were also invited to present or share slides and other information in the afternoon about their comparisons. Early-career researcher Hao Guo presented an invited talk on 3D attenuation tomography, to encourage the community to think about tradeoff of attenuation and stress drop.

OUTCOMES OF WORKSHOP 2 and INTER-WORKSHOP PROGRESS

By the conclusion of the workshop, the group agreed to continue working on their methods, share spectra and more detailed results from a handful of selected events, and embark on two benchmark studies.

- Benchmark study #1: Spectral fitting exercise. Chu will create source spectra for the 55 events using a GIT approach and distribute those source spectra. We ask participants to fit the spectra, or create spectral ratios and then fit, to determine f_c and M_0. This will help us to determine how much variability is arising simply from different fitting algorithms or assumptions (such as type of spectral model or bandwidth).
- New subset of 8 events for careful study. In the few weeks following the workshop, Chu and Abercrombie will choose a handful of earthquakes from the 55 for very detailed study and ask participants to submit as much information as possible.

WORKSHOP 3 OVERVIEW. The January 26, 2023 Stress Drop Validation TAG workshop was held virtually on Zoom from 9am to 3pm, attended by 76 people (from 10 countries spread over 3 continents). By Workshop 3 in January 2023, we received several new and some updated submissions for a total to date of 28 submissions from 18 research groups. The workshop started with the usual welcome and introductions (wherein all participants typed their name, institute and location into Zoom chat simultaneously!) from Annemarie, and background and progress to date on the TAG from Rachel. In this, we showed compilations of the most recent overall results, focusing on differences between the two general methods (eGf deconvolution and generalized inversion method). We then turned it over to those who had submitted results to each present a few slides on their approach to uncertainties, parameter trade-off, and inter-method comparison, with a focus on the 8 selected earthquakes. Session 2 kicked off with an invited talk from Jamie Neely on his recent work *Assessing the Accuracy of Earthquake Stress Drop Estimation Methods for Complex Ruptures Using Synthetic Earthquakes*, and then segued into some detailed comparison of the 8 events, in which we tried to generate future ideas for the TAG. One focus for this workshop was to move on from identifying the differences between submitted stress drop results from individual studies, to trying to identify the most important causes of these discrepancies. To do so we quickly pulled the presented information (spectra, estimated values, etc) from each of the presenters, on each of the 8 selected events, into one slide deck that we compared together. In this, we started to get a sense of some events consistently showing higher or lower stress drop, or more or less source complexity.

Session 3 was designed to engage the broader community, informing users of the reliability and limitations of current seismological measurements and seeking input that can help guide us forward as we seek to improve the types of source parameter measurements we make, and their precision. The session generated broader discussion on the uses of stress drop beyond our direct community, with a focus on ground motion and hazards implications, as well as source physics implications, The format was two sets of short talks and panel discussion: the first was

on ground motion and hazard implications, with 5-minute talks by Gail Atkinson and Tara Nye, comments from Rob Graves, and then some discussion; and, the second with 5-minute talks from Elisa Tinti, Greg McLaskey and Nadia Lapusta on source physics implications. We then briefly went over the results from Benchmark #1: Spectral Fitting and closed with future directions and next steps for the TAG.

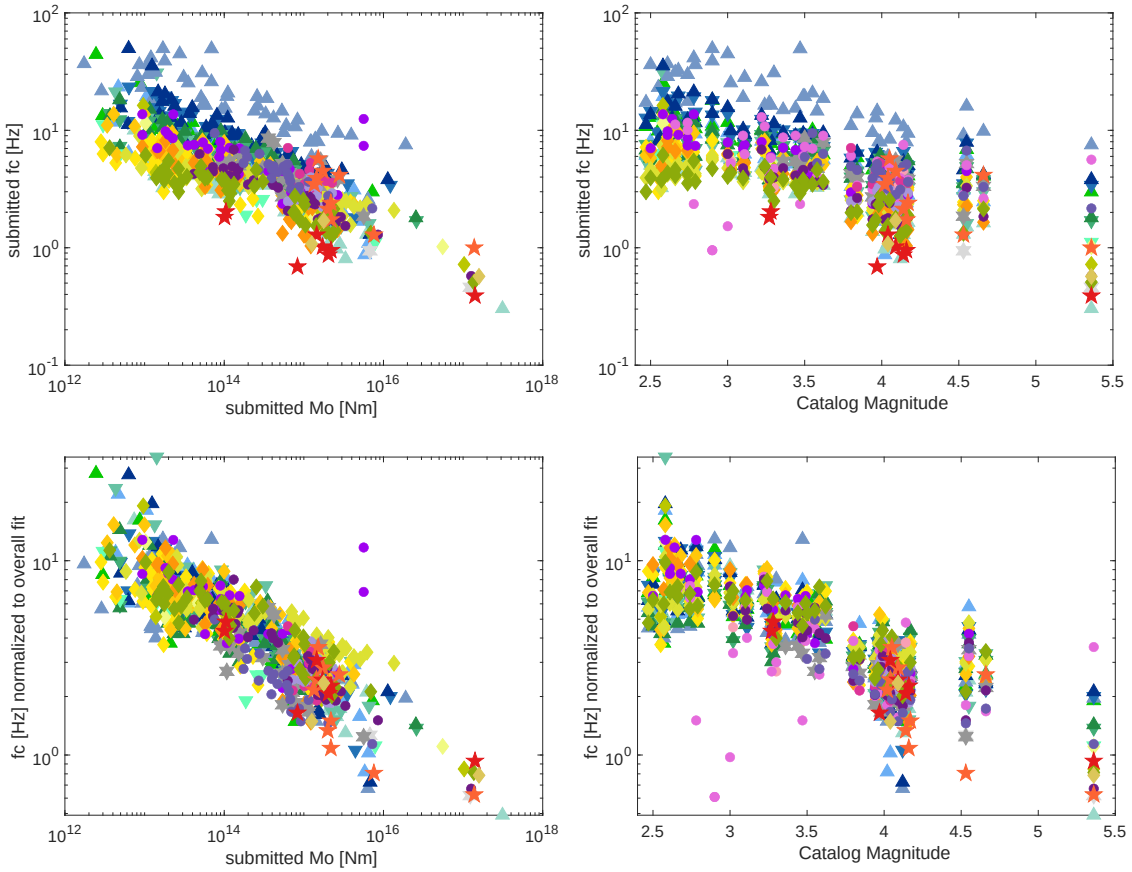


Figure 1. Corner frequency and seismic moment (Mo) submitted by different authors (shown anonymously as different symbols) for Workshop #3 in January 2023. Corner frequency (fc) submitted (top row) and shown normalized by removing a single offset value for each author (bottom), compared to the estimated submitted Mo (left) and catalog magnitude (right). A reduction in scatter is evident when normalizing for each author, and tradeoff between fitted fc and Mo compresses the scatter in left panels as compared to right panels.

RESULTS COMPARISON: Leading up to each workshop, we have encouraged new or updated submissions, with a focus on a subset of 55 events, and specifically 8 events for which we solicited additional information (spectra or finite fault inversions). We requested results submission via a Google form and template spreadsheet ahead of the workshop so that we can analyze the results for each workshop.

Submitted results are sorted into four general methodological categories: (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 – Ground motion based methods; filtered amplitudes; single station; and combination methods.

Leading up to each workshop, PIs Abercrombie, Baltay and Chu performed comparison of the results, including considering the submitted stress drops, corner frequencies (fc) and moments (Mo), as well as other parameters such as duration, radius and energy (Figure 1). When comparing the estimated moments to catalog, we notice both consistent differences as well as random noise, tradeoffs are apparent in the fitting of moment and fc, such that there is overall less scatter when plotting fc vs moment as compared to catalog magnitude (Figure 1, top).

We recalculated stress drop using a consistent *Madariaga* (1976) model (k=0.21), with a single value of beta to avoid variability due to multiple stress drops or different beta values. We correlated all submissions with all others, finding some similar methods correlate well, including those by authors who have been collaborating. We also considered catalog vs. calculated moments and magnitudes, assuming the *Hanks and Kanamori* (1979) relation between seismic moment and moment magnitude.

We considered that different authors, methods or implementation of such might have different bias, or offsets, so we removed an average constant-stress drop offset from each submission. After adjusting for this, we see much less overall variability (Figure 1, bottom), so one future point of research is to understand if there are physical or methodological reasons for the average offset of each author.

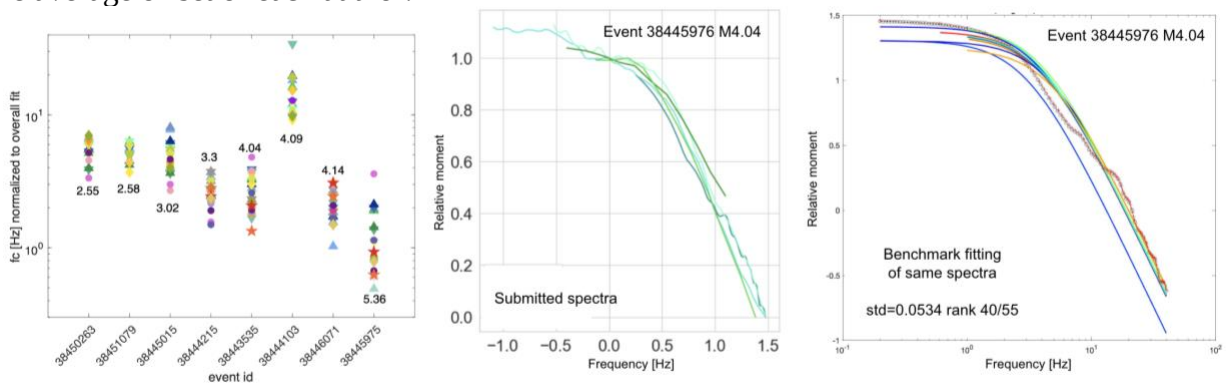


Figure 2. (left) Author-adjusted corner frequency for the 8 selected events. (middle and right) Example spectra for one of the selected events. (middle) Submitted event spectra from several different groups (anonymously shown in different colors). (right) Benchmark fitting exercise in which participants fit provided spectra from the same event, to understand variability from the fitting alone, and tradeoffs in fitting fc and Mo. Fitted Brune spectra shown anonymously in different colors.

For Workshop #3, we honed in on the 8 selected events (Figure 2). After adjusting for the overall author offset, the variability within each event is reduced to a point where differences in fc between events is evident. Work is thus needed to understand the physical cause of different author biases. Many participants also submitted source spectra for the 8 events (Figure 2 middle) which we could compare to see agreement or disagreement in shape or amplitude. We also received submissions from Dreger et al. of finite fault slip patches. There are some events that are simpler and show more agreement between authors, and several with more complex or variable spectra.

Lastly at Workshop #3, we discussed the results from Benchmark #1: Spectra Fitting (Figure 2 right). Even starting from the same provided spectra, there is variability in fitted parameters by different participants, and clear tradeoff in M_0 and f_c, which are both affected by

how the low frequencies are constrained. Over the whole set of 55 events, we found variability arising from spectral fitting is about 25-30% of total event variability. We plan to perform other benchmarks to isolate contributions from other components.

Although we see disagreement between the estimated parameters, perhaps we can use this variability as an indicator of physical complexity: Do simpler, more ideal events generally display more agreement in stress drop, while more complex events less? By comparing the collected event spectra with the Dreger et al. finite fault inversions, we see some examples with a relative simple circular slip patch and pulse-like source time functions correspond to smooth, more Brune-like spectra and relatively agreement in the estimated f_c and M_0 by the various groups. For an event that shows more variability in the estimated parameters, there is a clear "bump" in the spectra indicating multiple rupture patches, and the slip inversions indeed indicate multiple patches and complex source time functions at some stations. So the relative variability of estimated stress drop between submissions may be an indicator of physical complexity.

FUTURE TAG DIRECTIONS. One main goal of both workshops 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 by individuals, including sharing more methodological details and further refinement of methods.
- Consideration of physical reasons for overall differences, magnitude trends, and depth trends between different authors. We plan to iterate with authors so they can investigate why their results are offset from the average.
- Recommendations on best practices for different aspects of the problem as we have learned from the comparative analysis, such as what effect fitting in linear vs. logarithmic space has on the fitted parameters, and how we can potentially constrain the long-period (moment) level of fitting to remove that part of variability.
- Future benchmark studies, such as the effect on results of varying both time windows and frequency bands used in analysis. A second benchmark is provide record spectra for many events to be used in the analysis.. We will use FFT or mtspec (or similar) to create record (station) spectra for many events. This will help us to determine how much variability is arising from differences in methods to convert time series to the frequency domain.

Organizational directions:

- Continued monthly-ish Zoom meetups.
- Seismica overview by Baltay, Abercrombie, Chu and Taira is in review.
- Special issue of either SRL or BSSA for the entire TAG study, with individual papers by contributors on methods, and several comparison papers.
- Special session at SSA Annual Meeting for the TAG (led by Colin Pennington) and associated happy hour gathering in San Juan.
- Consideration of the best way to share results between the group, to promote collaboration but respect individuals' different desires on sharing information.

REFERENCES

Hanks, T. C., and H. Kanamori (1979). A moment magnitude scale, *J. Geophys. Res. B Solid Earth* **84**, no. B5, 2348–2350, doi: 10.1029/JB084iB05p02348.

Madariaga, R. (1976). Dynamics of an expanding circular fault. Bull. Seismol. Soc. Am., 66, 639–666.

APPENDIX A: WORKSHOP #2 AGENDA and PARTICIPANTS

SATURDAY, SEPTEMBER 10, 2022, Palm Springs Hilton

09:00 - 10:00	Check In, coffee and Networking by the pool bar	
10:00 - 12:30	**Session 1: Welcome and Background**	
10:00 - 10:15	Welcome, Introductions	Annemarie Baltay, Rachel Abercrombie and Shanna Chu
10:15 - 12:30	Method Lightning Talks	*All analysts*
12:30 - 13:30	*Lunch - box lunches available at the pool bar*	
13:30 - 15:30	**Session 2: Comparison of Results**	
13:30 - 13:45	Attenuation tomography and implications for source analysis	Hao Guo
13:45 - 14:00	Details of 6 focus events	Rachel Abercrombie and Shanna Chu
14:00 - 15:30	Analysts present comparison details, tradeoffs, attenuation	All - everyone invited to present for 5 minutes
15:30 - 16:00	*Networking Break*	*All*
16:00 - 17:00	**Session 3: Future Plans; Discussion**	
17:00	Workshop Adjourns	

Optional group dinner in Palm Springs at 7pm, TBA and not included.

WORKSHOP #2 PARTICIPANTS (31 total; * 6 on Zoom)

Rachel Abercrombie (Boston U)
Ralph Archuleta (UCSB)
Annemarie Baltay (USGS)
Yehuda Ben-Zion (SCEC/USC)
Glenn Biasi (USGS)
*Dino Bindi
Oliver Boyd (USGS)
*Xiaowei Chen (TAMU)
Shanna Chu (USGS)
Elizabeth Cochran (USGS)
*Bill Ellsworth (Stanford)
Wenyuan Fan (SIO/UCSD)
Hao Guo (U Wisconsin-Madison)
*Tom Hanks (USGS)
Rebecca Harrington (Ruhr U-Bochum)
Chen Ji (UCSB)
Junle Jiang (U Oklahoma)
Trey Knudson (Stanford)
Paul Martin Mai (KAUST)
Kevin Mayeda (AFTAC)
Morgan Moschetti (USGS)
*Arjun Neupane (U Tulsa)
Tara Nye (USGS)
Colin Pennington (LLNL)
Aaron Peyton (UCSB)
Peter Shearer (UCSD)
*Mariano Supino
Ian Vandevert (UC San Diego)
Bill Walter (LLNL)
Jeong-Ung Woo (Stanford)
Baoning Wu (USC)

APPENDIX B: WORKSHOP #3 AGENDA and PARTICIPANTS

THURSDAY, JANUARY 26, 2023 *VIRTUAL on ZOOM*
All times below are Pacific Standard Time (PST or UTC-8).

09:00 - 09:30 Introduction (Rachel Abercrombie / Annemarie Baltay PDF, 4.8MB)

09:30 - 11:00 **Session 1**: Discussion on uncertainties and trade-offs, with focus on 8 events- led by presentations from submission contributors. (combined PDF, 4.1MB)

- Comparison of spectral decomposition & eGf spectral ratio methods (Shanna Chu)
- Measuring Source Parameters using Peak Amplitudes (Bill Ellsworth & Trey Knudson)
- eGf Spectral Ratio (Colin Pennington)
- Multi-Method Comparison (Kevin Mayeda)
- Spectral Ratios - Choice of EGF, Time Window etc. (Rachel Abercrombie)

- Ridgecrest P and S spectral decomposition comparisons (Peter Shearer & Ian Vandevert)
- Agreement in Seismic Moment between MT solutions and S wave Source Spectra (Chen Ji)
- Estimating stress drop from P-wave spectra (Peter Shearer)

11:00 - 12:00 *Break*

12:00 - 13:00 **Session 2**: Discussion and lightning talks, and ideas for future study.

- Assessing the Accuracy of Earthquake Stress Drop Estimation Methods for Complex Ruptures Using Synthetic Earthquakes (Jamie Neely)
- Introduction: Radiated Energy (Shanna Chu)
- Discussion of 8 events (Annemarie Baltay, Rachel Abercrombie)

13:00 - 13:30 *Break*

13:30 - 15:00 **Session 3**: Broader community invited talk session. Wrap up.
Ground motion and hazard implications
- Some Remarks on Stress Drop (Gail Atkinson)
- Site-Kappa Estimates in the San Fransisco Bay Area (Tara Nye)
- Remarks by Rob Graves

Source Physics implications
- Brune Stress Drop vs. Finite Fault Stress Drop Estimates (Elisa Tinti)
- How Lab Scientists Use Seismology (Gregory McLaskey)
- Presentation by Nadia Lapusta

15:00 *Workshop Adjourns*

APPENDIX B: WORKSHOP PARTICIPANTS (76 total)

Rachel Abercrombie (Boston)
Pablo Aravena (SLU)
Ralph Archuleta (UCSB)
Gail Atkinson (Western U)
Annemarie Baltay (USGS)
Michael Barall (USGS)
Oliver Boyd (USGS)
Sara Cebry (Cornell)
Xiang Chen (GFZ)
Xiaowei Chen (Texas A&M)
Shanna Chu (USGS)
Elizabeth Cochran (USGS)
Rebecca Colquhoun (U Oxford)
Luis Dalguer (3Q-Lab)
Ahmed Elbanna (UIUC)
Bill Ellsworth (Stanford)
Wenyuan Fan (sio/ucsd)
Art Frankel (USGS)
Alice Gabriel (UCSD)
Robert Graves (USGS)
Hao Guo (U Wisconsin-Madison)
Tom Hanks (USGS, retired)
Jeanne Hardebeck (USGS)
Ruth Harris (USGS)
Behzad Hassani (BC Hydro)
Grégoire Heller (CEA)
Joanna Holmgren (U Bristol)
Yihe Huang (U Michigan)
Tran Huynh (USC/SCEC)
Chen Ji (UCSB)
Debi Kilb (Scripps, UCSD)
Brian Kilgore (USGS)
Chi-Yu King (Retired)
Trey Knudson (Stanford)
Neha Kumari (ISR, Gandhinagar)
Nadia Lapusta (Caltech)
Guoqing Lin (U Miami)
Itzhak Lior (Tel Aviv U)
David Lockner (USGS)
Martin Mai (KAUST)
Kevin Mayeda (AFTAC)
Gregory McLaskey (Cornell)
Reza-gene Milani (USGS)
Pamela Moyer (U New Hampshire)
Jamie Neely (Northwestern)
Arjun Neupane (U Tulsa)
Tara Nye (U Oregon)
Daniel Ortega-Arroyo (MIT)
Adrien Oth (ECGS)
Sunny Park (U Chicago)
Grace Parker (USGS)
Edric Pauk (USC)
Colin Pennington (LLNL)
Matteo Picozzi (U Naples)
John Rekoske (UCSD)
Hugo Sanchez (IRD)
Natalie Schaal (CSUN)
Cassandra Seltzer (MIT)
Peter Shearer (UCSD)
Jun Young Song (Cornell)
Will Steinhardt (UCSC)
Mariano Supino (INGV)
Taka'aki Taira (UC Berkeley)
Gabrielle Tepp (Caltech)
Elisa Tinti (U La Sapienza)
Ana María Tobón López (ISTerre)
Daniel Trugman (Nevada Seismo Lab)
Takahiko Uchide (GSJ, AIST)
Ian Vandevert (Scripps, UCSD)
William Walter (LLNL)
Jeremy Wong (Scripps, UCSD)
Tiange Xing (MIT)
Simone Yeager (USGS)
Clara Yoon (USGS)
Jeena Yun (Scripps, UCSD)
Yijian Zhou (UC Riverside)

Report for SCEC Award 23108: 2023 Community Stress Drop Validation Workshop