REPORT
doi:10.26443/seismica.v3i1.1009

SEISMICA

The SCEC/USGS Community Stress Drop Validation Study Using the 2019 Ridgecrest Earthquake Sequence

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Abstract We introduce a community stress drop validation study using the 2019 Ridgecrest, California, earthquake sequence, in which researchers are invited to use a common dataset to independently estimate comparable measurements using a variety of methods. Stress drop is the change in average shear stress on a fault during earthquake rupture, and as such is a key parameter in many ground motion, rupture simulation, and source physics problems in earthquake science. Spectral stress drop is commonly estimated by fitting the shape of the radiated energy spectrum, yet estimates for an individual earthquake made by different studies can vary hugely. In this community study, sponsored jointly by the U. S. Geological Survey and Southern/Statewide California Earthquake Center, we seek to understand the sources of variability and uncertainty in earthquake stress drop through quantitative comparison of submitted stress drops. The publicly available dataset consists of nearly 13,000 earthquakes of M1 to 7 from two weeks of the 2019 Ridgecrest sequence recorded on stations within 1-degree. As a community study, findings are shared through workshops and meetings and all are invited to join at any time, at any interest level.

Production Editor:
Gareth Funning
Handling Editor:
Stephen Hicks
Copy & Layout Editor:
Hannah F. Mark

Received:
June 23, 2023
Accepted:
April 25, 2024
Published:
May 22, 2024

Non-technical summary The stress release (or stress drop) during an earthquake provides information on how geologic forces are converted to radiated seismic energy when a fault ruptures, and the conditions under which an earthquake will continue to increase in size or trigger earthquakes nearby. Stress drop is also an important element of seismic hazard mapping and building design, since high stress drop earthquakes radiate more high frequency energy, resulting in stronger ground shaking. Unfortunately, stress drop estimates made in different studies have large systematic and random differences, implying that they are not as reliable as we need for use in ground motion prediction and earthquake source physics research. We introduce a Community Stress Drop Validation Study in which we invite all interested scientists from the international community to analyze the same earthquakes and compare and contrast their results. We use a public dataset of recordings of aftershocks of the 2019 Ridgecrest, California earthquake. Our aim is to understand where the differences and similarities in stress drop come from, and then work with the wider user community to develop improved methods for characterizing earthquake rupture and the resulting ground motions for more reliable and informed earthquake hazard forecasts.

1 Introduction

"What is earthquake stress drop, and what does it represent physically?" is a long-standing, open question in earthquake physics (e.g., Abercrombie, 2021). Seismologists and ground-motion modelers often mean dynamic stress drop, the change in shear stress driving earthquake faulting that goes into radiated seismic energy, which controls the amplitude and frequency content of ground shaking during earthquakes and is thus of great interest to ground-motion modelers and structural engineers. Geologists often mean static stress drop, the change in average stress resolved onto the fault before and after an earthquake rupture, which controls the mechanics of crustal deformation and should be related to slip on a fault, which can feed into earthquake occurrence statistics. In idealized, theoretical earthquake models, static and dynamic stress drops are equivalent: the dynamic high-frequency stress drop that can be measured from the radiated far-field seismogram is the same physical parameter as the static low-frequency stress drop that relates earthquake moment to rupture area.

To first order, this equivalency between various stress drop definitions and estimates has been observed, suggesting that earthquakes rupture in approximately the same way in a variety of geologic settings and over a wide range of magnitudes. This allows us to extrapolate current models and knowledge to predict ground-motion, slip, recurrence rates and other parameters to poorly recorded large-magnitude events, close distances, or new regions of interest. To improve our understanding of earthquake rupture dynamics, and de-

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termine the factors that control earthquake rupture nucleation, propagation and arrest, we need to understand the real variation in earthquake stress drop (see Abercrombie, 2021).

Typically, seismologists estimate an average spectral stress drop $\Delta\sigma$ for an earthquake from the recorded Fourier frequency-amplitude spectrum by first fitting an ideal displacement source spectrum *u(f)*, with *f* the frequency, as a function of seismic moment (M_o) and corner frequency (f_c)

$$u(f) = \frac{M_0}{\left[1 + \left(\frac{f}{f_c}\right)^{n\gamma}\right]^{\frac{1}{\gamma}}} \quad (1)$$

where *n* is the high-frequency falloff rate and γ governs the shape near the corner. The commonly-used Brune (1970) model has *n*=2 and $\gamma = 1$. Then $\Delta\sigma$ is simply derived from the estimated corner frequency and moment, assuming a circular crack (Eshelby, 1957):

$$\Delta\sigma = cM_o \left(\frac{f_c}{k\beta}\right)^3 \quad (2)$$

where *c* is a constant accounting for rupture geometry (7/16 for a circular rupture) and k depends on the rupture velocity, wave type, and source model (typically 0.2-0.3, e.g., Brune, 1970; Madariaga, 1976; Sato and Hirasawa, 1973; Kaneko and Shearer, 2015). The corner frequency is inversely proportional to the wavelength of peak radiated energy from the source. Thus, stress drop can be thought of as the link between the low-frequency estimates of seismic moment and the high-frequency radiated energy assuming simple Brune-type circular crack models (Brune, 1970; Madariaga, 1976) in which corner frequency is inversely proportional to the rupture radius. Other source models are also possible, such as (Boatwright, 1978) with *n*=2 and $\gamma = 2$ in Eq. 1) or double corner models where the low-frequency f_c is related to the source duration and hence dynamic stress drop discussed herein, and the higher f_c is related to a secondary process such as rise time, starting or stopping phases, or a dynamic weakening process (e.g., Denolle and Shearer, 2016),

Throughout our study, and in this paper, we focus on this widely used spectral estimate of stress drop, whether it comes directly from the corner frequency or a related parameter, such as duration, energy, or high-frequency ground motion. While the alternate name of "stress parameter" is in use to describe the source spectral shape in ground motion modeling (i.e., Atkinson and Beresnev, 1997), due to the large uncertainties and difficulties relating it to any actual stress drop in the earth, here we use the simple term "spectral stress drop" for spectral estimates to match current practice. Apparent stress, defined as rigidity times the ratio of broadband radiated seismic energy to moment, is theoretically a more model-independent estimate of the stress drop (e.g., Ide and Beroza, 2001; Baltay et al., 2010). In practice, however, accurate measurement of radiated broadband energy is challenging as it requires extrapolation to high frequencies, and often depends on the same spectral modeling as the spectral stress drop estimates, because of the need to model high-frequency attenuation and other path effects. These measurements are especially difficult at the higher frequencies required to quantify radiated energy of smaller earthquakes (e.g. Abercrombie, 1995; Ide and Beroza, 2001; Abercrombie, 2021). This spectral stress drop is an average stress drop over an earthquake rupture, and the relationship between that average and time- and space-varying stress drop on a fault is not always well resolved (Noda et al., 2013). Similarly, the details of the relationship between this seismological spectral stress drop and the actual stress release on a fault or numerical simulations are poorly understood (e.g., Kaneko and Shearer, 2015; Ji et al., 2022). Before we can attempt to connect all these parameters, we need to first ensure our estimate of the spectral stress drop is reliable and reproducible; this is the aim of the community study.

The ease with which it can be measured and its importance for both earthquake physics and high-frequency ground-motion modeling, have led to spectral stress drop becoming a frequent subject of study worldwide (e.g., Aki, 1967; Hanks, 1977; Abercrombie, 1995; Ide and Beroza, 2001; Baltay et al., 2011; Abercrombie et al., 2016). However, for as long as stress drop has been measured, it has been a topic of debate, as stress drop estimates are rife with uncertainties and appear highly variable (Cotton et al., 2013; Abercrombie, 2021).

While we often observe an approximately constant range of stress drop over a wide range of earthquake magnitudes, the variation within individual studies can be three orders of magnitude (e.g., Figure 1). How much of this is due to measurement uncertainty, and how much to real inter-event variation is unknown. For individual earthquakes, stress drops estimated by different researchers or using different methods rarely agree (e.g., Abercrombie, 2013; Pennington et al., 2021), with differences between estimates larger than the reported uncertainties, implying that calculated uncertainties of at least some approaches must be significantly underestimated. On a larger scale, it is still an open question as to whether stress drop scales with magnitude (e.g., Baltay et al., 2010; Bindi et al., 2020), depth (e.g., Hardebeck and Aron, 2009; Trugman and Shearer, 2017; Abercrombie et al., 2021), faulting regime or tectonic setting (e.g., Allmann and Shearer, 2009; Boyd et al., 2017; Huang et al., 2017), or even nature and extent of dynamic weakening or thermal pressurization (Beeler et al., 2012; Nielsen et al., 2016; Rice, 2006). However, the large scatter currently obscures these trends, so for stress drop to be most reliably used both to understand rupture physics and in models and simulations, we need to understand how physical processes, methodological differences, and data processing artifacts contribute to these variations.

Various studies have investigated the effects of differences in methods or data selection, including Shearer et al. (2019), Goertz-Allmann and Edwards (2013), Abercrombie (2015), Chen and Abercrombie (2020), Pennington et al. (2021), and Shible et al. (2022); Abercrombie (2021) provides a broad review of the difficulties, uncertainties and methods in stress drop estimation and comparison. These studies found that although methodological differences can lead to some systematic biases, the main differences come from the simplifying assumptions and model parameterization, and the limited quality and quantity of the data. Objectively determining the most reliable approaches for calculating stress drop, and more representative estimates of uncertainties, is beyond the abilities of any individual group.

Awareness of the need for a community-wide study to resolve these discrepancies has been growing over the years (e.g., Baltay et al., 2017; E.C.G.S. Workshop, 2012). Therefore, this Community Stress Drop Validation Study was initiated by co-leads Annemarie Baltay and Rachel Abercrombie in 2021, with support from the U.S. Geological Survey (USGS) and Southern California Earthquake Center (SCEC); the Statewide California Earthquake Center (SCEC) continues to support this project in 2024. The goals of this group are to understand: (1) the sources of agreement or difference between different methods and data sets used in estimating stress drop, (2) how physical attributes of the earthquake source affect the variability or degree of agreement of those estimates, and (3) ultimately, what is the best path forward for measuring stress drop and characterizing the high frequency radiation for various end-user needs. The 2019 Ridgecrest earthquake sequence provides the perfect dataset for such a comparative study.

2 Research priorities and organization

2.1 Research priorities

The goals of this Community Stress Drop Validation Study are to understand the nature and causes of variability and uncertainty in spectral earthquake stress drop estimates and how physical effects, random errors, differing data sets and methodological variability may contribute to these discrepancies, so that we best understand and account for these uncertainties.

Our specific research priorities are to:

1. Understand how different methods and assumptions lead to variations in estimated stress drop and predicted high frequency radiation. Do certain methods highlight different frequency aspects of the source? How do data selection and preprocessing affect the results? How are different analysts implementing methods?

2. Determine how variations in the estimated spectral stress drops reflect physical variations in earthquake source processes or material properties. Do simpler or smoother events yield more agreement between stress drop estimates while complex events show more variability? How do these stress drop estimates depend on the physical size, depth, location or tectonic setting of the earthquake?

3. Develop best practices for estimating a measure of spectral stress drop that can reliably be used in ground motion and hazard modeling, and by the wide community seeking to understand earthquake source physics and dynamic rupture processes (including laboratory work and numerical modeling). Ultimately, the best way to estimate stress drop may vary between events depending on factors such as its tectonic setting, inferred rheological properties and rupture behavior, but can we develop a baseline method that is consistent for a particular type of earthquake?

2.2 Study organization

The overall process for the Stress Drop Validation Study is to: provide and distribute a common dataset from the 2019 Ridgecrest sequence; solicit community researchers to carry out analyses of stress drop, or related parameters, for those events; return results of these analyses to the project leads for systematic comparison and meta-analysis; and discuss and disseminate these findings through scientific conferences, workshop discussions, and publications. In addition to attracting participants to make measurements, a major aim of the group is to engage end users to promote informed use of observational measurements with understanding of the uncertainties, and also assist in developing and making the most useful measurements needed to advance hazards and earthquake physics research. This study is envisioned as an iterative and community-driven process to help the seismological community strengthen our understanding of stress drop variability and uncertainty, and what it can tell us about the physics of earthquake rupture and the resulting ground motions.

This project has focused on building community and encouraging collaboration between participants to stimulate validation efforts, leading to sub-groups performing comparative analysis, and investigating the effects of method variations (e.g., Bindi et al., 2023a,b). Through support from SCEC, we have hosted three virtual workshops in November 2021, January 2023 and January 2024, and one in-person workshop at the SCEC Annual Meeting in September 2022. The virtual workshops have attracted over 100 participants each from 20 countries and all continents (except Antarctica), while the more focused in-person workshop was 30 participants. At each workshop, recent results and meta-analysis are shared, and the group discusses future directions including also hearing from stress drop users, rather than just analysts. At the most recent January 2024 workshop, for example, we discussed creation and analysis of synthetic datasets, hearing about several different methods for simulating waveforms (full workshop reports can be found at https://www.scec.org/research/stress-drop-validation). In between workshops, we hold ~monthly video-conference calls for community building and validation activities, which are typically held at two different times in the same day to encourage and enable global contributions; we currently have broad geographical participation.

3 Current validation study: 2019 Ridgecrest earthquake sequence

The current community stress drop validation study is focused on the 2019 Ridgecrest earthquake sequence

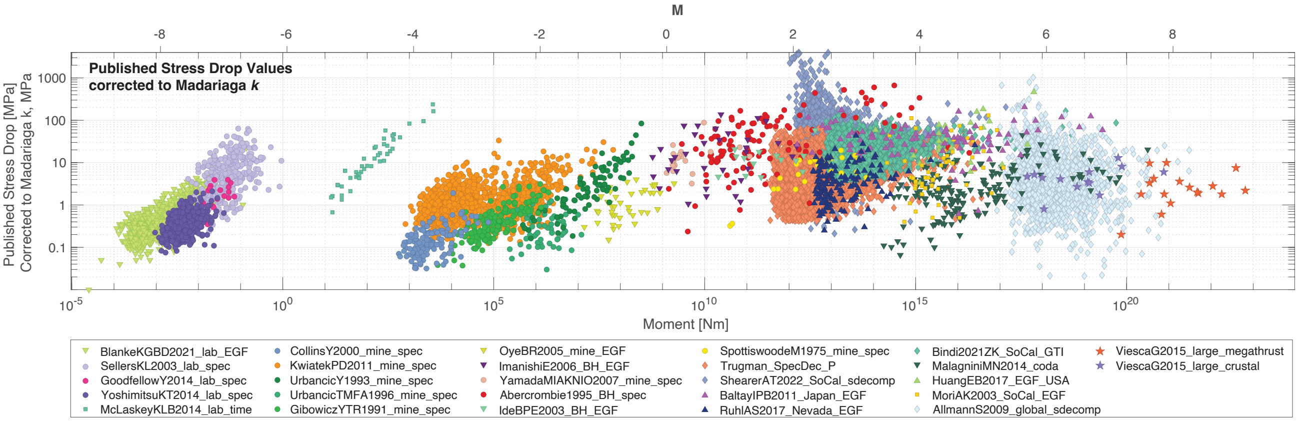

Figure 1 Published stress drop compilation showing stress drops versus magnitude for global earthquakes across a wide range of magnitudes. For each study, the stress drop is corrected assuming the *k=0.*21 value from Madariaga (1976), to avoid discrepancies purely from author choice of *k*. While there is very large scatter between and across studies, stress drops are generally bounded between 0.1 and 100 MPa, for events ranging from acoustic emissions recorded in the lab and during mine-break experiments, (Yoshimitsu et al., 2014; Sellers et al., 2003; Kwiatek et al., 2011; Spottiswoode and McGarr, 1975; Urbancic et al., 1996; Urbancic and Young, 1993; Gibowicz et al., 1991; Collins and Young, 2000; Oye et al., 2005; Yamada et al., 2007; Goodfellow and Young, 2014; Blanke et al., 2021; McLaskey et al., 2014), to regional studies (Abercrombie, 1995; Imanishi and Ellsworth, 2006; Trugman, 2020; Shearer et al., 2022; Bindi et al., 2021; Malagnini et al., 2013; Baltay et al., 2011; Huang et al., 2017; Ide et al., 2003; Mori et al., 2003; Baltay et al., 2010; Ruhl et al., 2017) and global compilations (Allmann and Shearer, 2009; Viesca and Garagash, 2015).

using a set of common waveforms. The study is divided into two main research activities: 1) Independent analysis of stress drop for the Ridgecrest sequence by researchers, and submission to the group validation repository; and 2) Meta-analysis to compare the submitted results. The study is inclusive and iterative, in that any researchers may join at any time to provide their estimates of stress drops; then as a group we compare all stress drop estimates and refine the stated problem and narrow the data set to best achieve our goals. Individual researchers will then repeat some aspects of their analysis with newfound insight and using a more limited data set.

We have created and provide a common data set for this study, including waveforms and metadata, available for download through the Southern California Earthquake Data Center: https://scedc.caltech.edu/data/stressdrop-ridgecrest.html, where a “Quick-reference guide” is also posted for more information on the waveform data. This dataset consists of ~13,000 earthquakes of magnitude 1+ over two weeks from July 4 until July 17 (Figure 2). This contains the M7.1 and M6.4 Ridgecrest mainshocks, three M5 earthquakes and 86 M4 events. This two-week window was chosen to avoid introducing selection biases yet retain a set of earthquakes sufficient for the wide variety of expected stress drop analyses. It is unlikely that any individual contributor will analyze all the earthquakes, and the approaches of different groups will be suitable for different subsets. To increase comparison, we have selected a subset of 55 events, by choosing well recorded events over a range of magnitudes from 2 to 4.5, at a range of depths and along different parts of the rupture. We ask researchers to prioritize these events in their analysis, if possible.

3.1 Waveform data

The provided data are recorded on 107 local and regional stations within 1-degree (~110km) of each epicenter, and consist of broadband velocimeter, accelerometer and geophone instruments—including both horizontal and vertical components. Data come from the Southern California Data Center (SCEDC), International Research Institutions for Seismology Data Management Center, and the Northern California Earthquake Data Center. We included network codes CE, CI, GS, NN, NP, PB, SN, and ZY but excluded the nodal network 3J, and used channels HH (up to 200 sps) and CH (> than 200sps) for broadband, HN (<200 sps) and CN (>200 sps) for accelerometers, and EP (<200 sps), EH (S200sps) and DP (>200 sps) for geophones (see Data and Code Availability section); in each case the channel with the highest sampling rate is chosen for co-located instruments. The length of each record is proportional to the magnitude, with the record starting 15s before the origin time (OT) and ending 60s after for M1; for the M6+ the records start 90 before OT and end 310s after. The waveforms are provided in miniSEED format and can be directly downloaded as tar files grouped by magnitude, to reduce file size for any one archive. Within each tar file is a folder for each earthquake; within that folder is a list of stations for that event, accompanying response information (SAC pole-zero files) and StationXML metadata. The ObsPy (Beyreuther et al., 2010) script used to create this dataset is available for use as well, either to facilitate direct download of the waveforms, or to adjust any of the parameters.

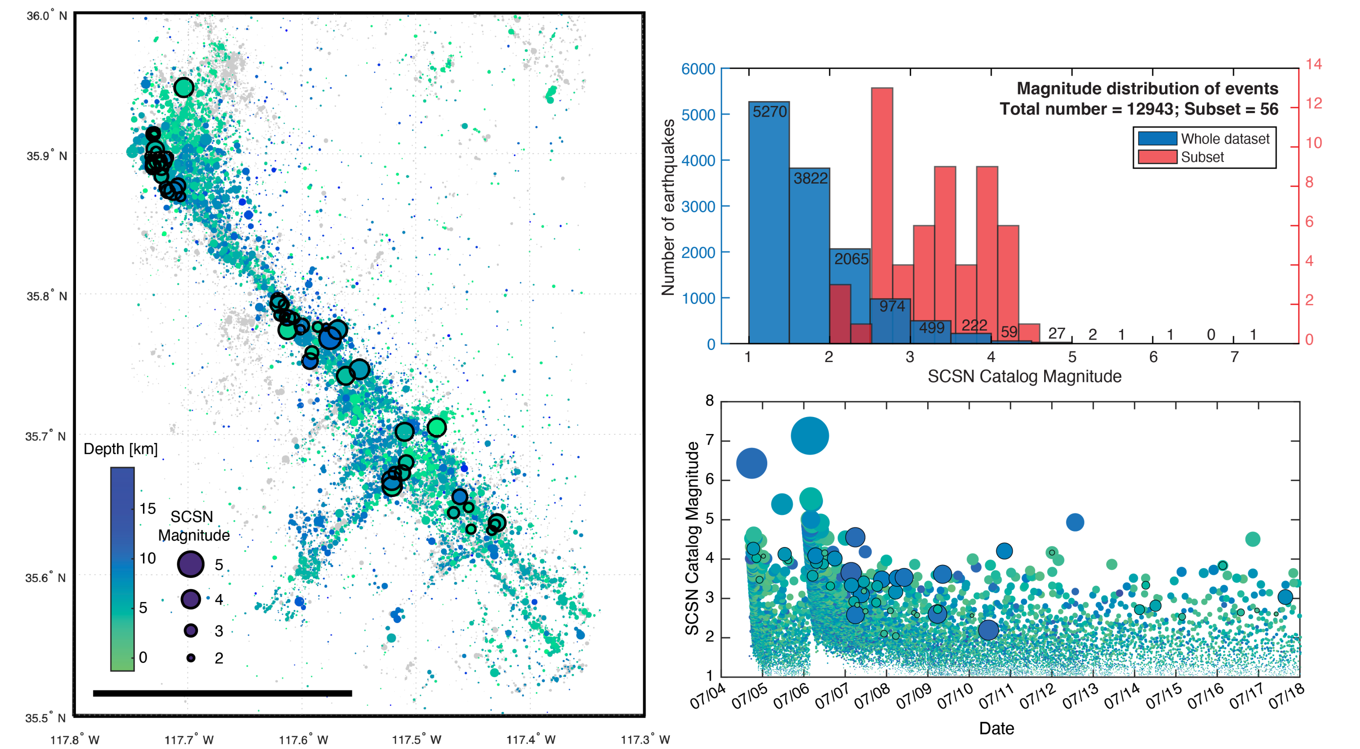

Figure 2 Event locations (left), magnitude (top right) and time-vs.-magnitude distribution (bottom right). Inset map shows location of Ridgecrest region (red box) within the state of California. Entire two-week relocated event catalog of ~13,000 earthquakes by Trugman (2020), shown in circles colored by depth and sized by magnitude and in blue histogram bars. Subset of 55 events for focused study shown encircled in black, and in red histogram bars.

3.2 Metadata

Along with the waveform data, we provide several metadata to assist in analysis, and remove unnecessary sources of variation between results.

- *Earthquake Catalog.* Full earthquake catalog with SCSN magnitudes and relocations from Trugman (2020).
- *P- and S-wave phase picks.* Initial P- and S-wave phase picks for each record (although if a method requires improved picks, participants are free to adjust or repick the data) through two methods: The first are the SCEDC phase picks, which are not available for all events or all stations; the second are theoretical travel time calculations using a 1D velocity model. Both sets of phase-picks are included batched into the .tar files with the waveforms.
- *V_s30 station estimates.* Time-averaged shear-wave velocity in the upper 30m (V_s30) for each station. The V_s30 values are preferentially measured, as reported by Yong et al. (2013); if direct measurements are not available then V_s30 is estimated based on the mosaic proxy of Heath et al. (2020).
- *Ridgecrest 1D velocity model.* A simple 1D velocity model for those wanting depth-dependent rupture velocity correction, developed by White (2021), by combining and discretizing the models from Lin et al. (2007) (25% weight), Zhang and Lin (2014) (25% weight) and White et al. (2021) (50% weight).

4 Earthquake stress drop analysis

4.1 Individual stress drop analysis

Throughout the study, we solicit submissions of stress drop or other source parameter estimates (source duration, finite fault inversions, high-frequency energy, etc.) in a defined spreadsheet format from the community via the email distribution list. New and updated submissions of results and participation are still encouraged, especially from students, early career, and international (non-US) participants. To participate in the community study, we ask that participants be willing to provide their analyses potentially ahead of publication, so that they can iterate on methods and analysis. This allows them to understand and isolate sources of discrepancy or variability in their analyses, which will both improve the quality and impact of their own publications and eventually better inform other community members about alternative approaches and possible outcomes. Submission of the results is made only to the authors (study PIs), to ensure confidentiality of the results. Participants are asked for their permission before any results are shown to the larger group or included in presentations. To date, we have received 47 unique submissions from 20 research groups.

The common methods of estimating spectral stress drop, and their limitations, are reviewed by Abercrombie (2021). The original, simplest method of fitting individual earthquake spectra to determine source, path and site (e.g., Thatcher and Hanks, 1973) is still in use (e.g., Kemna et al., 2021) but has proven to be poorly constrained (e.g., Ko et al., 2012). When sufficient quantity and quality of recordings are available, variations on two distinct approaches are currently preferred to isolate the source, and estimate corner frequency, source duration or stress drop, and they both can use body or coda waves (see Abercrombie, 2021). Variations and combinations of these have been used by participants in the Community Study to date, and the authors cited below have all submitted preliminary results at the time of writing.

1. Spectral Decomposition / Generalized Inversion: A range of different inversion strategies are now in use, commonly known as spectral decomposition or generalized inversion techniques (GIT), for example, Shearer et al. (2006), Chen and Shearer (2011), Pennington et al. (2021), Trugman (2020), Bindi et al. (2021), Devin et al. (2021), Vandevert et al. (2022). These inversions simultaneously invert large numbers of earthquakes and stations for stability to obtain single, station-averaged values. Obtaining absolute values of source parameters, including earthquake magnitude, requires assumption of a source model (typically a Brune-type spectrum) or a constraint on the average site effect, for example, assuming a flat response at a reference rock site. These inversions also incorporate an azimuthally independent attenuation structure, which is assumed to be either homogeneous (constant) or a simple function of travel time.

2. Empirical Green's Function (EGF) Analysis: In this empirical approach, a small, co-located earthquake is used as an EGF to remove path and site effects from the spectrum or seismogram of a larger target earthquake. The deconvolution requires no assumptions about path or site effects, and can be applied to individual pairs of events, at individual stations to enable investigation of azimuthal variation in the source radiation and path effects. It requires an independent estimate of seismic moment of one or both events, a source model with which to fit the corner frequencies (could be one as given in Eq. 1 or an assumption that the EGF event is flat to displacement in the relevant frequency range), and depends on the availability of an appropriate, well-recorded EGF earthquake, which significantly limits the number of events that can be studied using this method. The results also depend on the correctness of the EGF assumption, and research into the effects of EGF choice is ongoing (e.g., Abercrombie et al., 2016). Spectral ratios are usually calculated by direct division of the amplitude spectra, but the source time functions can be calculated either by complex spectral division or by time-domain inversion. To obtain source parameters, the spectral ratios are fit with a simple Brune-source model (e.g., Abercrombie et al., 2020; Kemna et al., 2021; Liu et al., 2020; Ruhl et al., 2017; Boyd et al., 2017; Chen and Shearer, 2011; Mayeda et al., 2007). Alternatively, a finite fault or other inversion can be used to model the source time functions (e.g., Dreger et al., 2021; Fan et al., 2022).

Many approaches in common usage are variations and combinations of these two. For example, the coda calibration tool approach (Mayeda et al., 2003) uses coda spectral ratios of one or two calibration events to constrain the path and site corrections for other individual events and Eulenfeld et al. (2021) combine coda wave estimation of attenuation with a generalised inversion of the direct wave spectra. Kemna et al. (2021) and Boyd et al. (2017) use cluster-based approaches to constrain individual spectral fitting and spectral ratio modelling, respectively. Supino et al. (2019) develop a probabilistic framework for the inversion, and Satriano (2022) uses an iterative approach, first fitting individual body wave spectra then refining the fits with station-specific average constraints.

Several methods are distinct from the two main approaches, such as Knudson et al. (2023) and Al-Ismail et al. (2023), who calculate the amplitude spectra at individual points from the amplitudes of narrow-band filtered seismograms. Baltay et al. (2019) use ground-motion intensities to directly estimate stress drop, and Ji et al. (2022) estimate stress drop based on radiated energy.

4.2 Initial results and meta analysis

Direct comparison of the stress drops submitted to the Community Stress Drop Validation study so far reveals considerable scatter, but some stronger correlation between results using similar methods. The relative variations between different earthquakes are more consistent across the various studies, than are the absolute values, in line with the results of Pennington et al. (2021). We also observe some systematic magnitude- and depth-dependent overall offsets between different authors' submissions. Overall, we observe a stronger increase of stress drop with earthquake source depth for methods that do not allow travel-time dependent attenuation to vary with source depth. This implies that some of the increased stress drop with depth may be due to tradeoffs with attenuation and near-source structure, consistent with the results of Abercrombie et al. (2021).

To date, we have focused primarily on the estimates of corner frequency, and many methods also estimate seismic moment. We see large scatter in estimated corner frequency and also some considerable scatter in moment; some studies find an increase in spectral stress drop with increasing moment, but a constant stress drop is within the uncertainties for most, if not all, results. Whether any magnitude dependence to stress drop is real, or a consequence of the frequency bandwidth, simplistic assumptions and method selections used (e.g., Abercrombie, 2021) is not yet clear.

Of the 47 unique stress drop submissions received so far, 21 are published (Figure 3): Trugman (2020), Shearer et al. (2022), Bindi et al. (2021) and Bindi et al. (2023b), the latter of which included 18 variations using different parameters. These results all show relatively

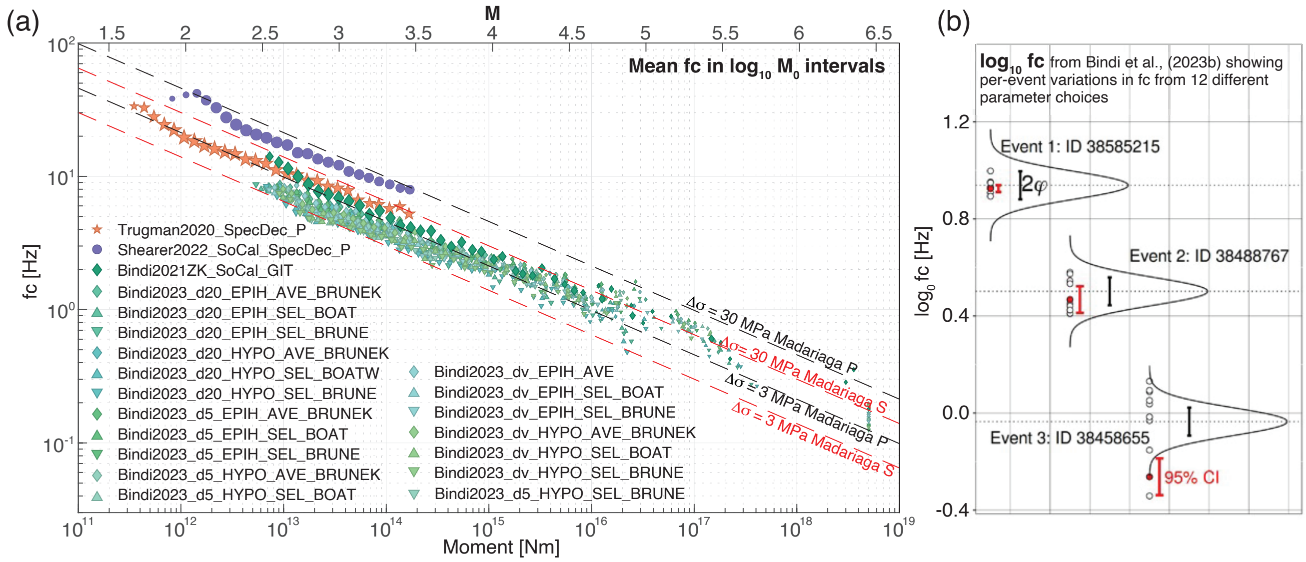

Figure 3 Comparison of published corner frequency results as part of the Community Stress Drop Validation Study. (a) Estimated corner frequency vs. estimated moment from Trugman (2020), Shearer et al. (2022), Bindi et al. (2021) and Bindi et al. (2023b), with dashed diagonal lines showing constant values of stress drop under the assumption of a Madariaga (1976) *k=0.21* for both P and S waves. (b) Comparison of resultant corner frequency from the 12 different parameter choices using a Brune (1970) spectra, from Bindi et al. (2023b) for three representative events (Event 1 M2.7; Event 2 M3.3; Event 3 M4.2). For the case shown in red filled circle and bar, the 95% confidence interval on that estimate sometimes doesn't overlap with the other estimates given other parameter choices. Figure (b) reproduced from Bindi et al. (2023b) Figure 6b.

constant stress drop scaling with magnitude (i.e., falling along a line of constant stress drop) and are recovering stress drops in a range of 3 to 30 Mpa, upholding expectations for regions in California. All these published results are large scale spectral decomposition/generalized inversion technique methods on the Ridgecrest 2019 sequence, so although these methods are very similar, there are significant systematic differences between them. Corner frequencies derived from P waves should be larger than those from S waves. While we see that estimates from both Trugman (2020) and Shearer et al. (2022), who use P waves, are indeed larger than those from the Bindi et al. (2021, 2023a,b) studies which all use S waves, the difference is larger than predicted by theoretical models; there is still significant offset between the two P-wave studies, similar to the range in the S-wave estimates obtained using different method variations. We need to further understand if there is a physical or simply methodological reason behind these discrepancies, and comparative studies such as Bindi et al. (2023a,b) are extremely valuable in determining the real systematic and random errors.

Bindi et al. (2023a,b) iterated over several parameter choices, including spectral window duration, source depth dependent or independent attenuation, different approaches for normalizing the site constraint, and fitting with a Brune (1970) or Boatwright (1978) spectral shape. For some specific events, the different corner frequencies estimated over these different iterations show good agreement (i.e., Event 1 in Figure 3b) while some events show large disagreement (i.e., Event 3). When considering the standard error of 95% confidence on one iteration, shown as the red bar in Figure 3b, sometimes the standard error encompasses the variability of the various iterations and sometimes does not, implying that method choices and assumptions can lead to wider variation than the formal errors in a single preferred approach, that are typically published. It remains to be seen if there are physical predictors or complexity that might indicate when estimated corner frequencies will agree or not.

We also find that a major source of disagreement stems from estimated seismic moments submitted for the same events. Many methods that generate displacement source spectra fit an estimated moment as well as a corner frequency, typically using a Brune (1970) spectra and fitting for the seismic moment M_0 as well as the corner frequency (Equation 1). Thus, there is inherent tradeoff in the two fitted parameters M_0 and f_c and we observe almost as much variability in submitted moments, as do submitted corner frequencies. We also convert the submitted moments to moment magnitude as $\mathbf{M} = \frac{2}{3}(log_{10}M_0 - 9.05)$, following Hanks and Kanamori (1979), and find both scatter and systematic differences between these **M** and the catalog moment magnitudes. The relationship between catalog measurements of local magnitude, coda magnitude, etc. and moment magnitude below M~4 is not simple (e.g., Hanks and Boore, 1984), and an incomplete understanding of magnitude can cause systematic bias in source parameter estimates as well as in statistical estimation of b-value, for example. However, the results compiled in this study provide a unique opportunity to improve moment-magnitude relationships in Southern California, and also potentially lead to a more physics based revised local magnitude scale (Mlr, https://scedc.caltech.edu/eq-catalogs/change-history.html).

5 Outlook

From the initial submitted and published results, it is apparent that more detailed analysis will improve understanding of why different methods and assumptions for estimating stress drop, or different researchers applying similar methods, yield different results. There are many places where workflows can differ, and so isolating how different choices affect the estimates, and which have the largest effects may improve coherency of results. Toward this end, it is encouraging to see many researchers within our community starting to study the sensitivity of estimated parameters to the various input choices (e.g., Bindi et al., 2023a), and initiating collaborations to compare approaches (e.g., Morasca et al., 2022).

To isolate and quantify specific sources of variability, we are conducting benchmark studies. In the first study, we are testing how results from different researchers vary even when they start out with the same source spectra. We have found that the variability in the benchmark fitting with fixed source spectra is about 3-10 times smaller when compared to overall results, indicating that spectral fitting is a small but relevant portion of the overall variability. Future benchmarks will enable us to isolate the effects of window length and frequency band selection, and other pre-processing choices. Providing an augmented dataset to include a processed ground-motion style flat file will facilitate participation of ground motion researchers in the study.

Joining the ongoing Community Stress Drop Validation Study is straightforward: one can download the data and perform analysis for stress drop, corner frequency or other source parameters, become involved in the meta-analysis to compare different results, or simply join in workshops to learn more about stress drop analysis or understand better how seismological measurements can constrain or inform their own research (https://www.scec.org/research/stress-drop-validation, or contact the authors). Even after this stage of the study is completed and published, the data and study description will enable future researchers to test and compare new methods and codes to existing methods.

Acknowledgements

The authors are very thankful for the community support in starting this effort, especially all those researchers who have contributed stress drop estimates, those who have participated in workshops and meetings, and everyone who has been a sounding board for this work, especially Bill Ellsworth, Tom Hanks, Elizabeth Cochran, Colin Pennington, and Greg Beroza. The authors thank the Southern California Earthquake Center and the new Statewide California Earthquake Center (SCEC) for providing the Technical Activity Group framework which made this effort a fully supported project; to the SCEC meetings team, especially Tran Huynh and Edric Pauk, without whom none of our workshops would be possible; the Southern California Earthquake Data Center (SCECDC) and others who helped with making the data set and meta-data and the whole SCEC community for their support. We thank Steve Hickman, German Prieto and editor Stephen Hicks for their thorough reviews of this manuscript. R.E. Abercrombie thanks the U.S. Geological Survey for funding to support this effort. S. Chu thanks Pacific Gas and Electric for support for this work. This research was supported by SCEC (awards 21083, 21114, 22101, 22042, 23107 and 23108 including salary support for T. Taira and financial support for the 2022 September workshop). SCEC is funded by NSF Cooperative Agreement EAR-1600087 & USGS Cooperative Agreement G17AC00047. SCEC Contribution #13444. Any use of trade, firm, or product names does not imply endorsement by the U.S. Government.

Data and code availability

All of the waveform data and metadata referenced herein are publicly available and accessed from the Southern California Earthquake Data Center (SCEDC), Incorporated Research Institutes for Seismology (IRIS) and Northern California Earthquake Data Center (NCEDC; doi:10.7932/NCEDC). The SCEDC (http://scec.org) is funded by National Science Foundation (NSF) Cooperative Agreement EAR-1600087 and USGS Cooperative Agreement G17AC00047. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the NSF under Cooperative Agreement EAR-1261681. Networks that provided data are: CE (California Geological Survey, 1972); CI (California Institute of Technology and United States Geological Survey Pasadena, 1926); GS (Albuquerque Seismological Laboratory, 1980); NN (University of Nevada, Reno, 1971); NP (U.S. Geological Survey, 1931); PB (https://www.fdsn.org/networks/detail/PB/); SN (University of Nevada, Reno, 1992); and ZY https://www.fdsn.org/networks/detail/ZY_1990/(Cochran et al., 2020). All data referenced here are available at the Southern California Earthquake Data Center (SCEDC, 2013) at https://scedc.caltech.edu/data/stressdrop-ridgecrest.html, where a "Quick-reference guide" is also posted for more information on the waveform data.

Competing interests

No competing interests.

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