Shanna Chu, comparison of spectral decomposition & eGf spectral ratio methods

- Data is pre-processed using the same selection criteria: window length, SNR above 3 in 10 frequency bands 1-40 Hz, P-wave
- For one method, I performed spectral decomposition with post-inversion constraint of the event spectra to a spatially-varying correction function derived from pinning stacked events in 0.2 magnitude bins to a Brune model.
- For the second method, I performed spectral ratios using an empirical Green's function. The eGfs are selected to be within 1 source radius of the target events (preliminarily calculated with 2.4 MPa stress drop) and minimum cross-correlation coefficient of 0.5.
- For spectral ratios, deviation from the Brune spectrum can be used to obtain peak-to-peak ratio, a proxy for source complexity which has variation across stations. The difference between GIT spectra (which uses all stations for an event) also shows a station-by-station difference to the spectral ratios.

Shanna Chu
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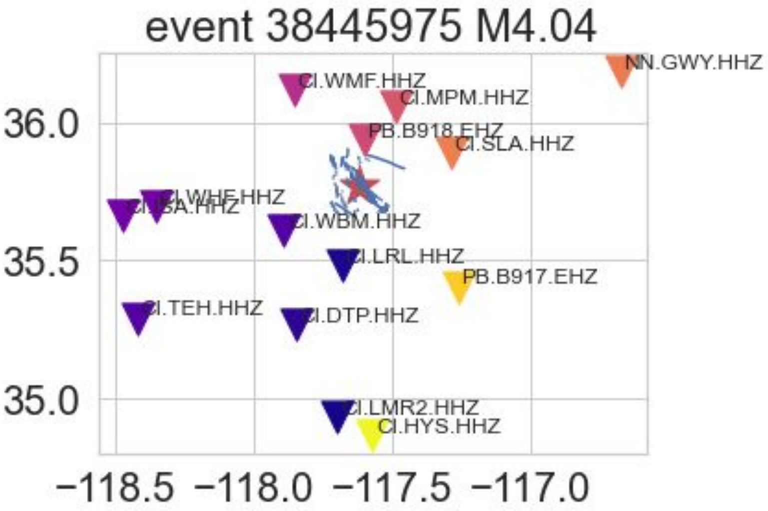
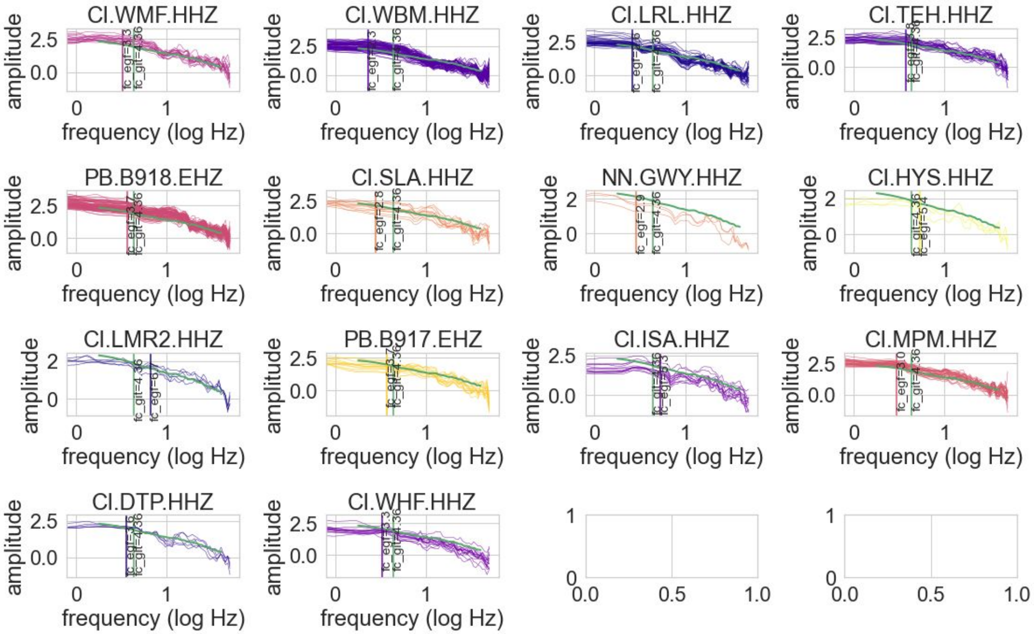
F_c ~ 4.3 with GIT and 2.9-5.7 Hz with eGf method. The two methods are closest at PB (borehole) stations.

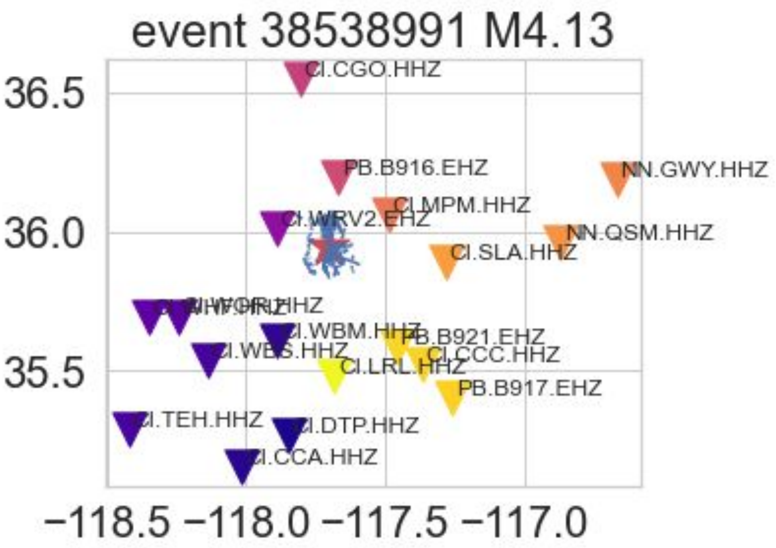
Chu

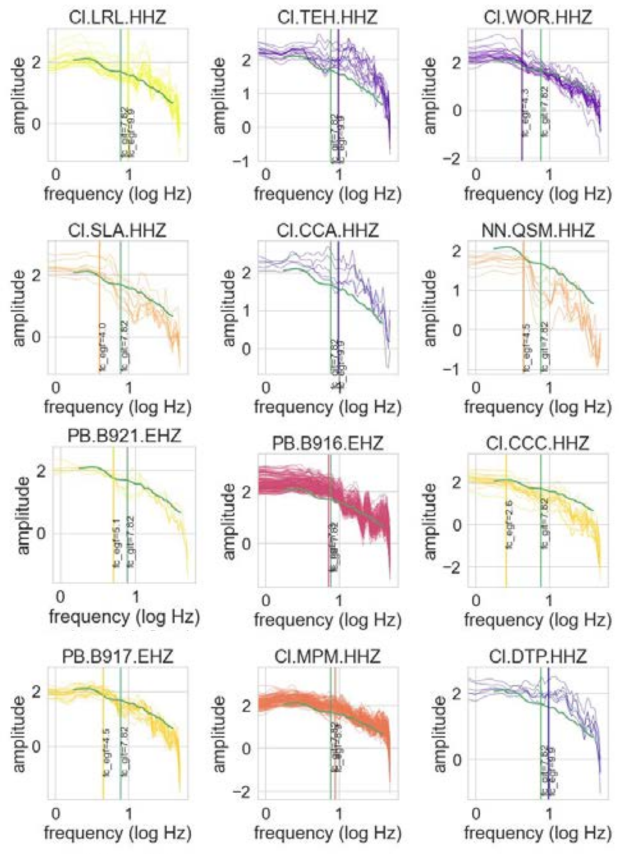




Some more figures, results, discussion

Chu





EXTRA SLIDES

38445975 M4.04 GIT fc=4.36 sd=25.04 MPa

38445975 M4.04 eGf fc=3.03 sd=6.58 MPa

38451079 M4.09 GIT fc=8.21 sd=104.58 MPa

38451079 M4.09 eGf fc=2.44 sd=4.07 MPa

38471103 M3.3 GIT fc=12.84 sd=18.76 MPa

38483215 M3.02 GIT fc=10.77 sd=8.09 MPa

38538991 M4.13 GIT fc=7.82 sd=79.01 MPa

38538991 M4.13 eGf fc=7.51 sd=136.3 MPa

38489543 M2.54 GIT fc=10.61 sd=1.97 MPa

Trey Knudsen and Bill Ellsworth
Measuring Source Parameters using Peak Amplitudes

- We measure the seismic moment and corner frequency of earthquakes using narrow band filtered peak displacement amplitudes. Errors are assessed using the bootstrap.
- "Richter"-like frequency dependent attenuation curves are used to correct for geometric spreading and anelastic loss.
- We have also estimated station corrections to the attenuation curves. These may account for path differences, site differences and radiation pattern.
- Results reveal a strong covariance of seismic moment and corner frequency.

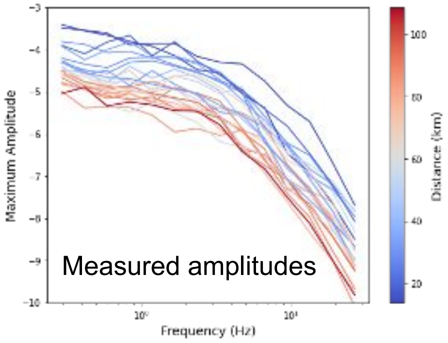
Trey Knudsen
Department of Geophysics Stanford University
trey05@stanford.edu

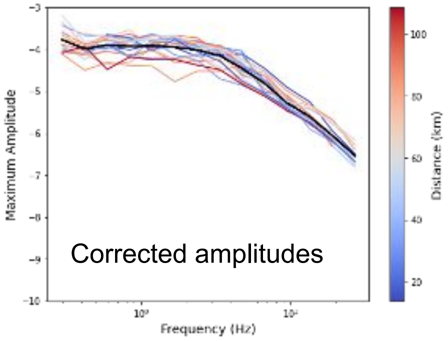
Bill Ellsworth
Department of Geophysics Stanford University
wellsworth@stanford.edu

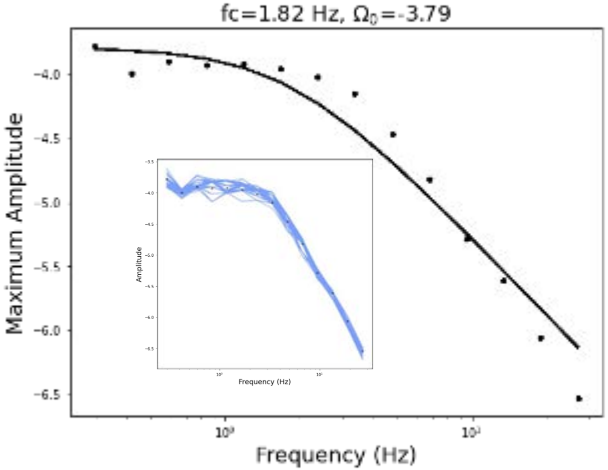
July 5 00:18 Mcat 4.04 ID 39445975

Knudsen and Ellsworth

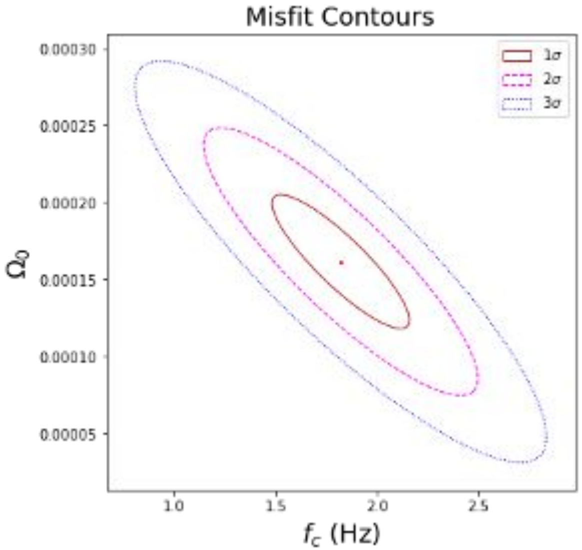
Mw 4.06, stress drop 9.0 MPa, fc 1.65 Hz







Best-fitting Brune spectrum
With bootstrap analysis



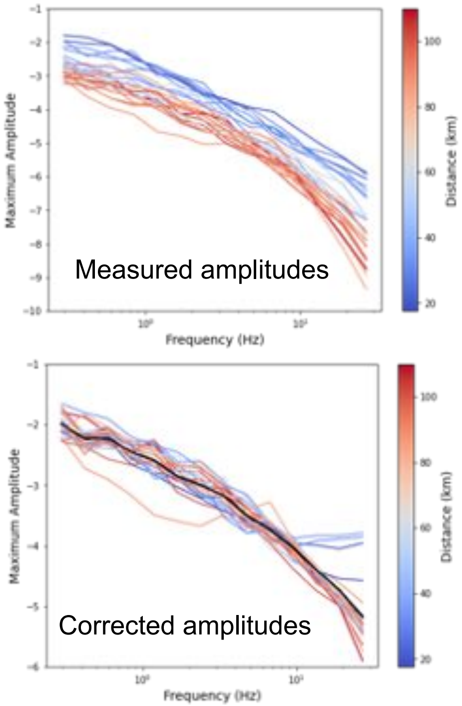
Misfit error analysis

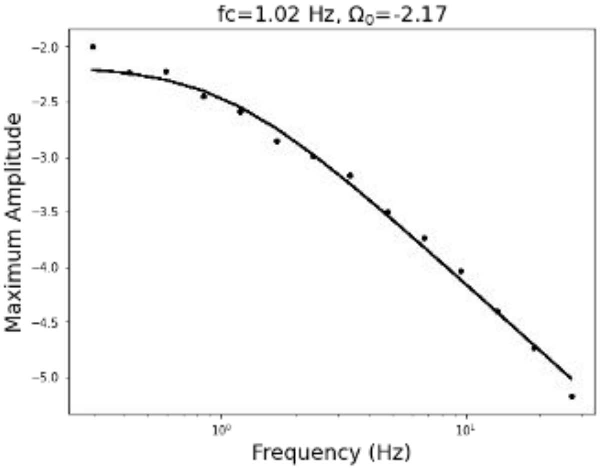
Note covariance between seismic moment and corner frequency

July 5 11:07 Mcat 5.36 ID 38450263

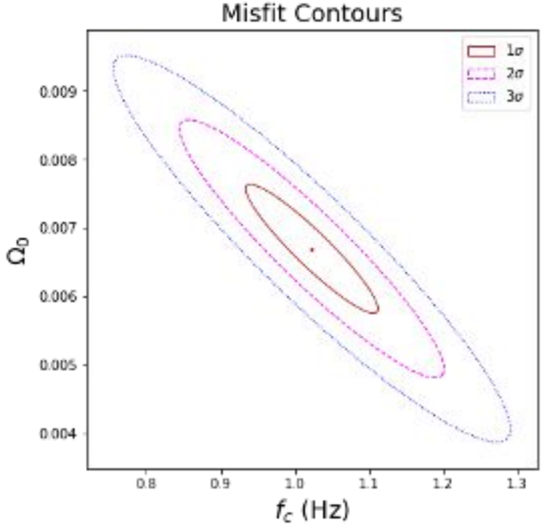
Knudsen and Ellsworth

Mw 5.13, stress drop 65 MPa, fc 1.02 Hz





Best-fitting Brune spectrum

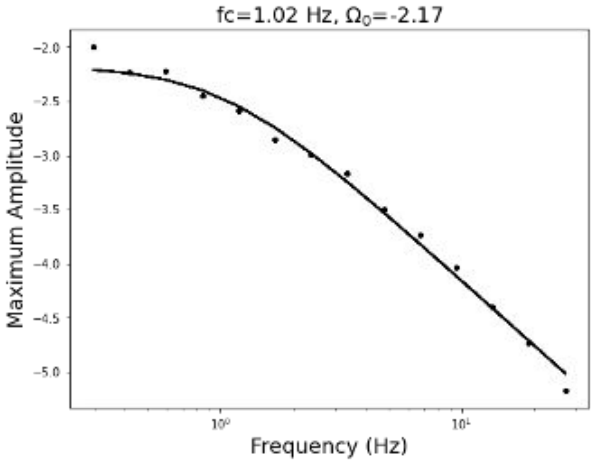


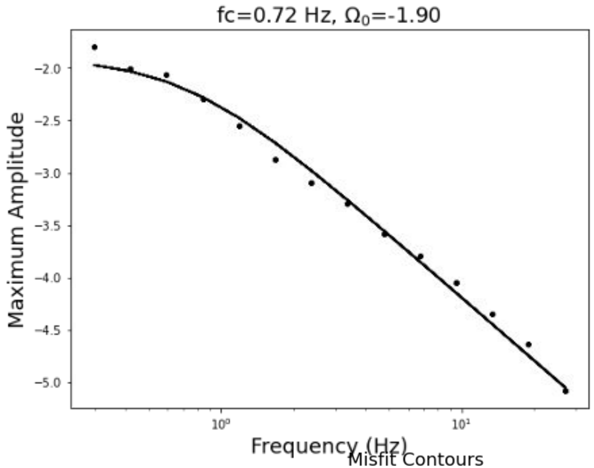
Misfit error analysis

Note covariance between seismic moment and corner frequency

July 5 11:07 Mcat 5.36 ID 38450263

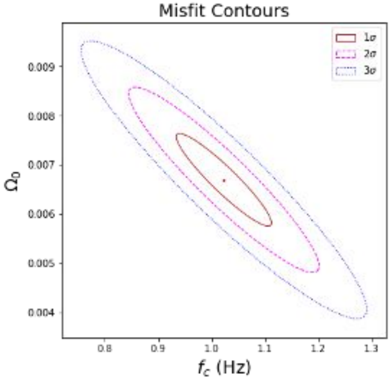
Knudsen and Ellsworth





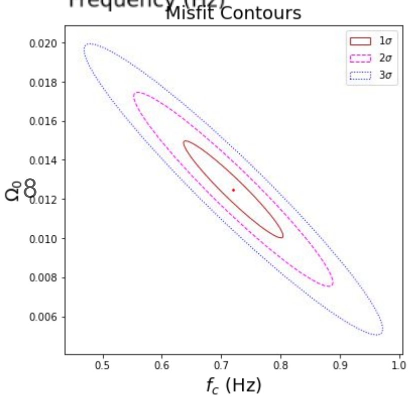
With station terms

Mw 5.13
fc 1.02 Hz
s.d. 65 MPa



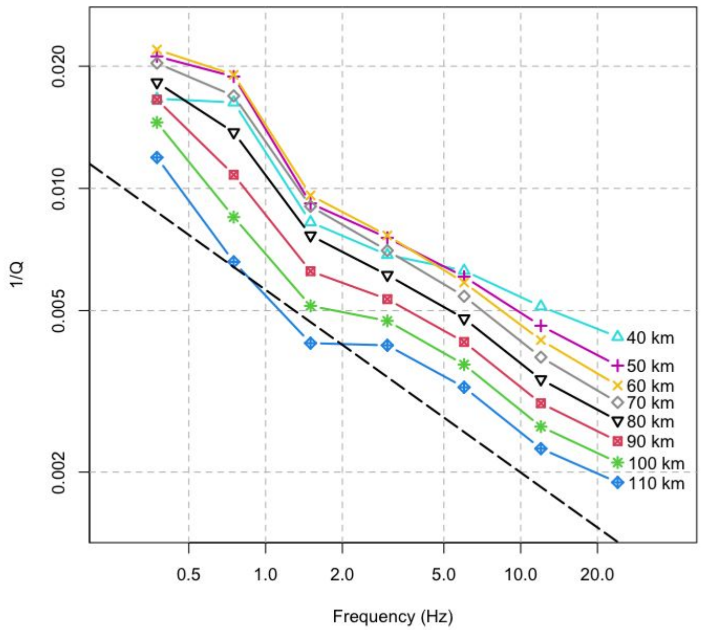
Without station terms

Mw 5.31
fc 0.72 Hz
s.d. 42 MPa



Frequency dependence of attenuation

From Al-Ismail, Ellsworth and Beroza (BSSA, 2023)



EXTRA SLIDES

Knudsen and Ellsworth

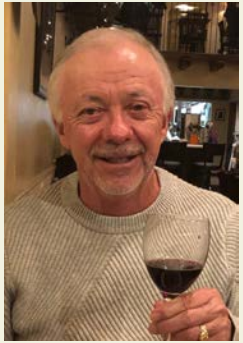
ID	depth	mag	date	time	log w0	fc	M0	Mw	stress drop
38445975	2.301	4.04	05-Jul-2019	00:18:01	-3.69	1.65	1.67e15	4.12	8.26
38451079	7.340	4.09	05-Jul-2019	12:38:30	-3.62	2.44	1.97e15	4.17	31.53
38471103	7.778	3.30	07-Jul-2019	03:23:26	-4.92	4.62	9.85e13	3.30	10.70
38483215	7.751	3.13	08-Jul-2019	05:02:10	-5.20	5.15	5.17e13	3.11	7.78
38450263	7.23	5.36	05-Jul-2019	11:07:53	-1.90	0.72	1.03e17	5.31	42.36
38538991	2.768	4.13	11-Jul-2019	23:45:18	-3.69	1.99	1.67e15	4.12	14.50
38489543	2.839	2.5	08-Jul-2019	17:30:03	-5.77	4.38	1.39e13	2.73	1.29
38496551	10.11	2.57	09-Jul-2019	05:17:45	-5.93	16.28	9.63e12	2.62	45.78



Multi-Method Comparison

Kevin Mayeda, Dino Bindi, Paola Morasca, Jorge Roman-Nieves, Bill Walter, Doug Dreger, Taka'aki Taira, Chen Ji, Ralph Archuleta

- CCT 2.3<*Mw*<6.9 (AFTAC, GFZ, INGV, LLNL *Mayeda et al.*)
- GIT 2.0<*Mw*<6.0 (GFZ, INGV, ECGS, U. Naples, *Bindi et al.*)
- Energy integration *Mw*> 4.0(UCSB *Chen Ji & Archuleta*)
- Finite Fault Inversion 3.3<*Mw*<5.53 (UCB *Dreger & Taira*)



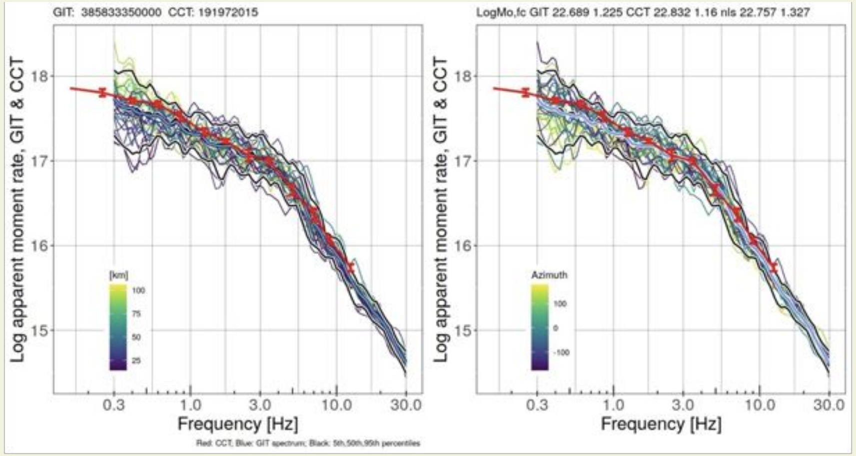
For common events from the initial focus events, recent extra events, and selected moderate magnitudes events, we find good correspondence for apparent stress and corner frequency for nearly all range of event sizes.

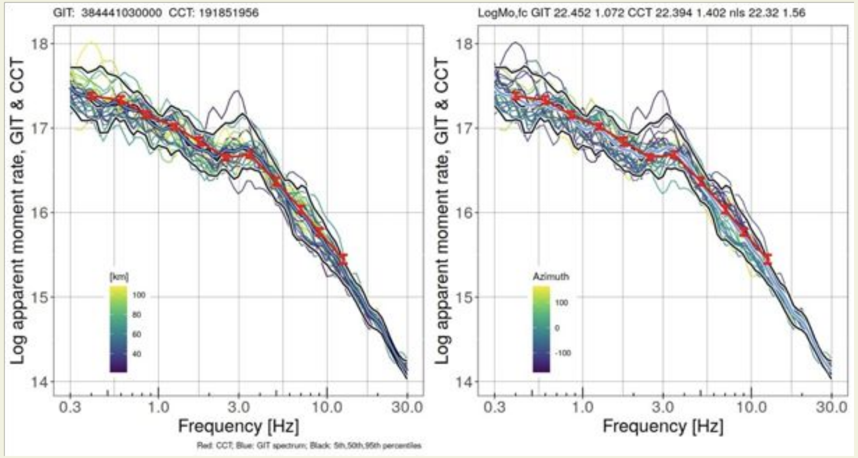
Kevin Mayeda, AFTAC,
kevin.mayeda@gmail.com

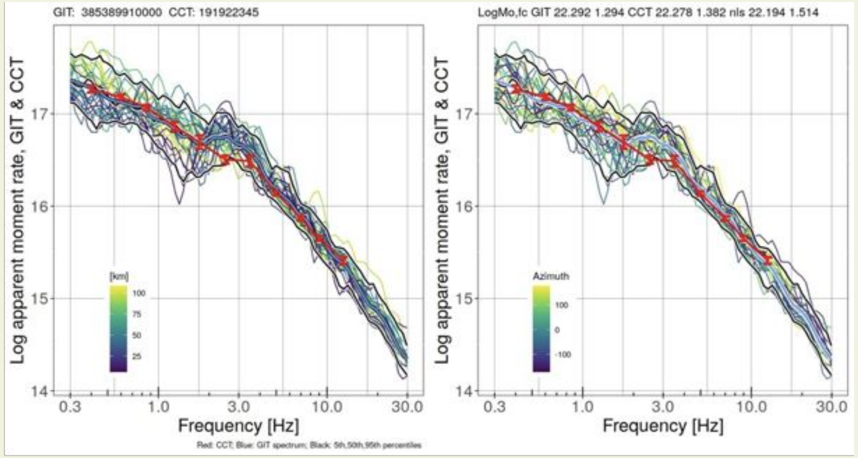


CCT vs GIT

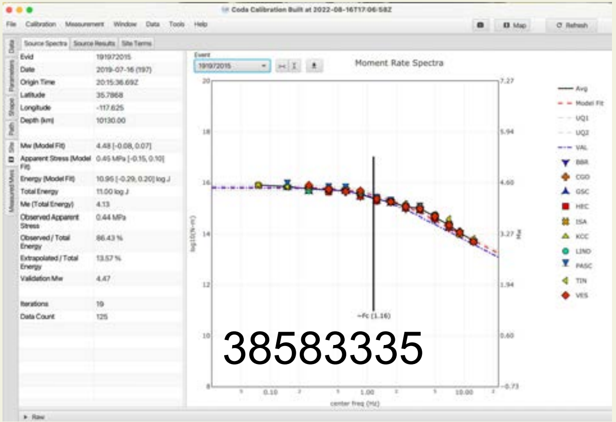
- 3 common 'Focus' events between GIT (*Bindi et al.*, 2021) and CCT spectra are in good agreement.
- 2 events (38444103, 38538991) show a pronounced spectral bump near 3-Hz.
- Correspondence between GIT and CCT also found in central Italy (*Morasca et al.*, 2022)

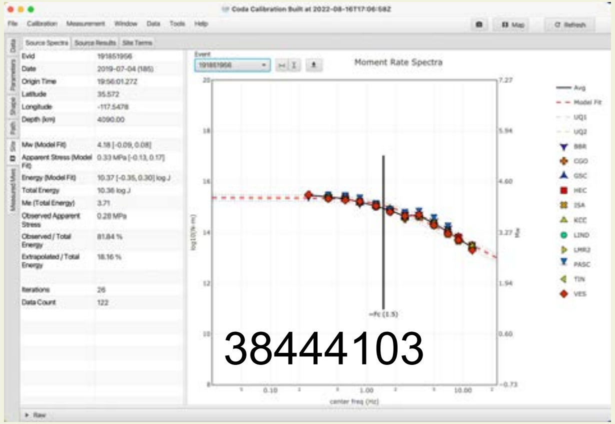


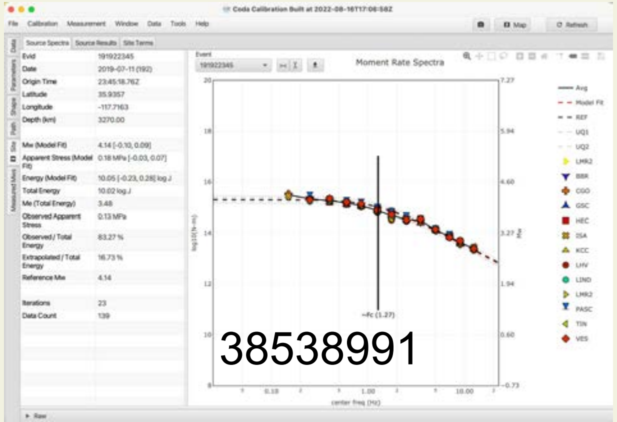


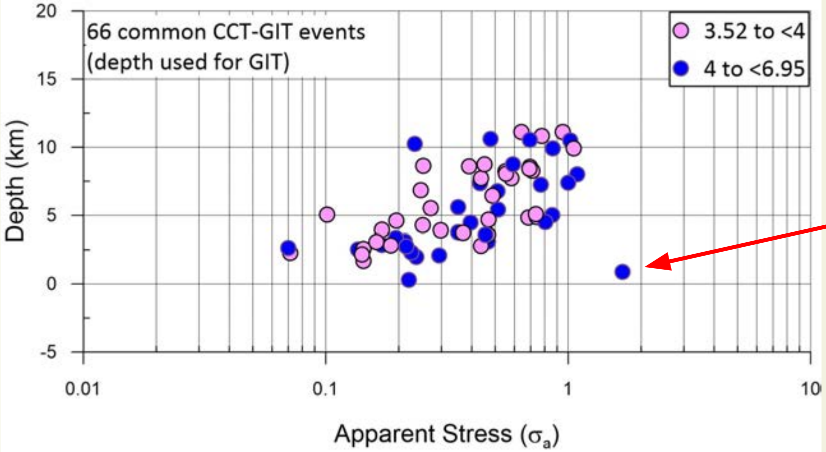


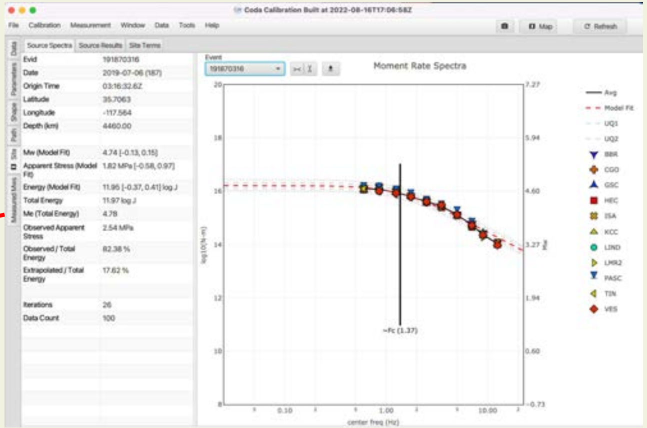
CCT Initial Focus events







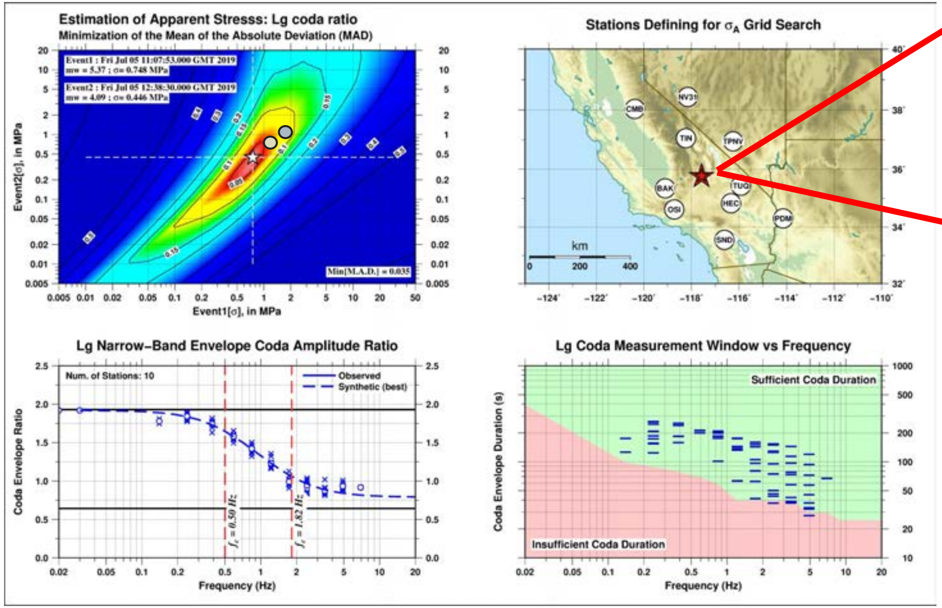


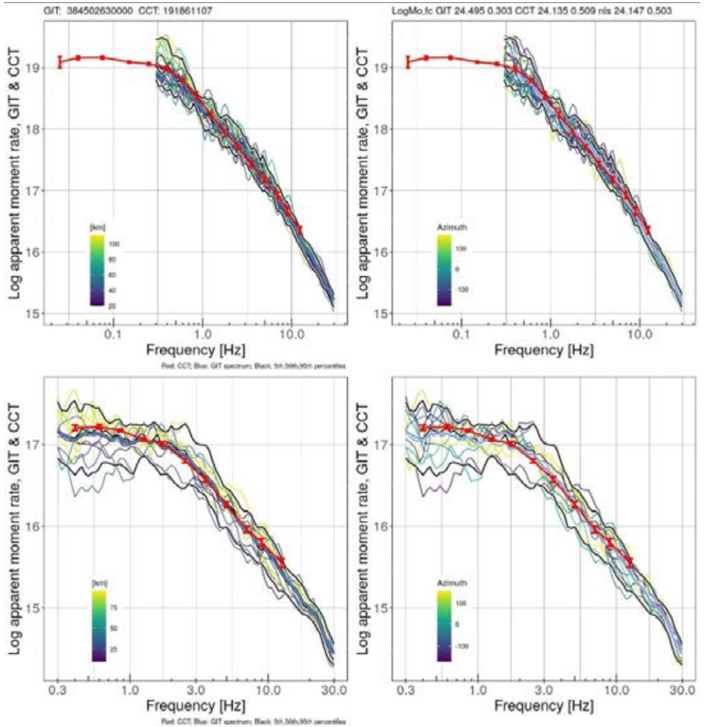


- CCT spectra for 3 Focus events.
- Depth dependence in apparent stress w/significant outlier 2019-07-06 03:16:32.

GT Source Constraints

CCT uses reference 'ground truth' (GT) spectra for site term corrections using the coda spectral ratio method (*Mayeda et al.*, 2007) avoiding *a priori* scaling assumptions.

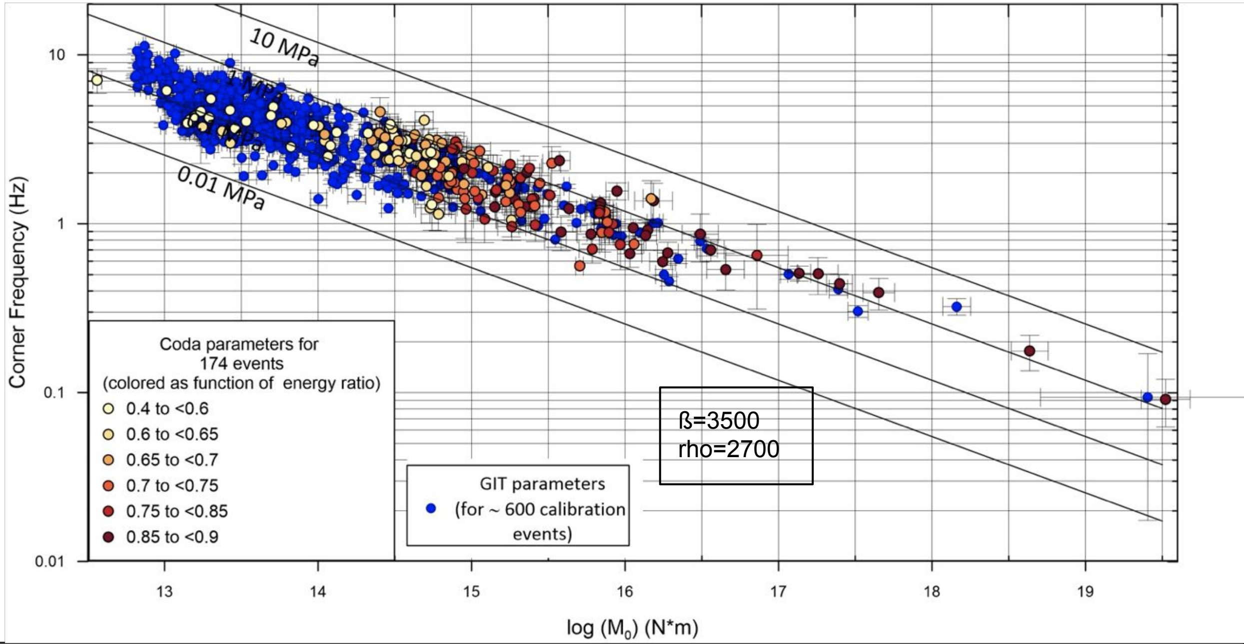




CCT and GIT spectra are in good agreement for an event pair used in determining GT source spectra used in the CCT calibration. These spectra along with independent *Mw*'s for other events provide the station site corrections.

Comparison of GIT vs Coda CT

- Spectra from GIT and CCT methods yield similar radiated energy, *Mw* and apparent stress.
- For the larger events, we find similar results with those from UCSB (*Ji & Archuleta*, pers. comm., Sept. 2022).



CCT vs GIT: GIT calibration events (~600 solid blue circles) from *Bindi et al.,* (2020;2021) and coda results are shown as white to deep red circles as a function of the ratio of observed to extrapolated energy (174 events) along with error bars derived from NLS inversion. Lines of constant apparent stress are shown as reference and similar to findings from central Italy by *Morasca et al.,* (2022).

Apparent Stress for Larger Events w/UCSB

- We compare results of 25 larger magnitude events also processed by UCSB (*Ji & Archuleta*) using three different methods.
- In general, agreement is good and future study to understand the outliers is planned.

Figure by Chen Ji and Ralph Archuleta:
GR: using the modified Gutenberg-Richter method (*Kanamori, et al*., 2020). Time domain, no local attenuation correction.
F0: frequency approach. Corrects near surface impedance, k_0, crust attenuation, similar to *Boatwright et al*. (2003). The
radiation coefficients are assumed to be 0.6 (*Boore and Boatwright*, 2003). It is on average 20% larger than GR.
F1: Similar to F0, except we use Caltech moment tensor to estimate radiation coefficients and only select the measurements with radiation coefficients larger than 0.25. It is on average 38% larger than GR.

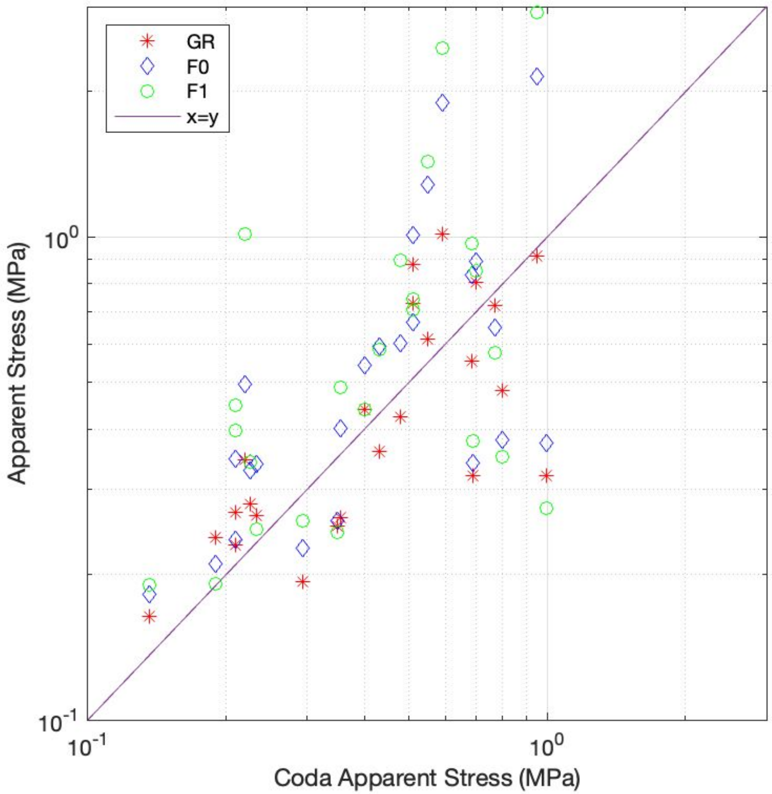


Table of solutions (EXTRA SLIDE)

EventID	Mw	Depth	Sta.	β_0(m/s)	ρ_0(kg/m^3)	f_c(Hz)	$\Delta\sigma_B$(MPa)	σ_a (MPa)	σ_a(CCT[1])	f_c(CCT)	f_c(Trugman[2])
38445975	4.0	2.30	12	3000	2650	1.08	0.50	0.21	0.16	1.54	
38450263	5.4	7.23	14	3650	2850	0.57	5.18	1.22*	0.89	0.51	0.57
38451079	4.1	7.34	12	3650	2850	1.70	1.53	0.61	0.49	1.78	
38538991	4.0	2.76	11	3000	2650	1.18	0.65	0.15	0.15	1.38	

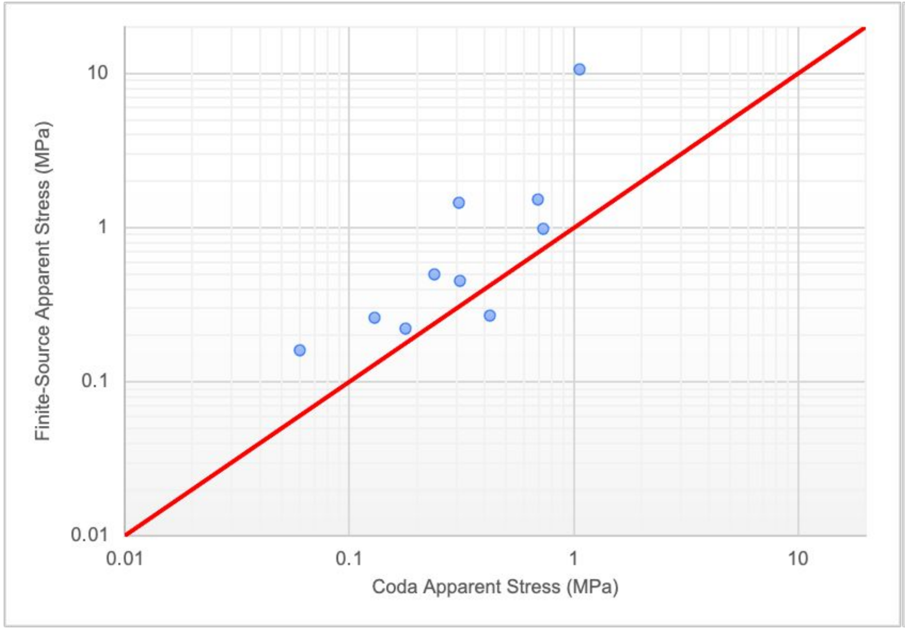
1 Values are adjusted to consider the rigidity difference

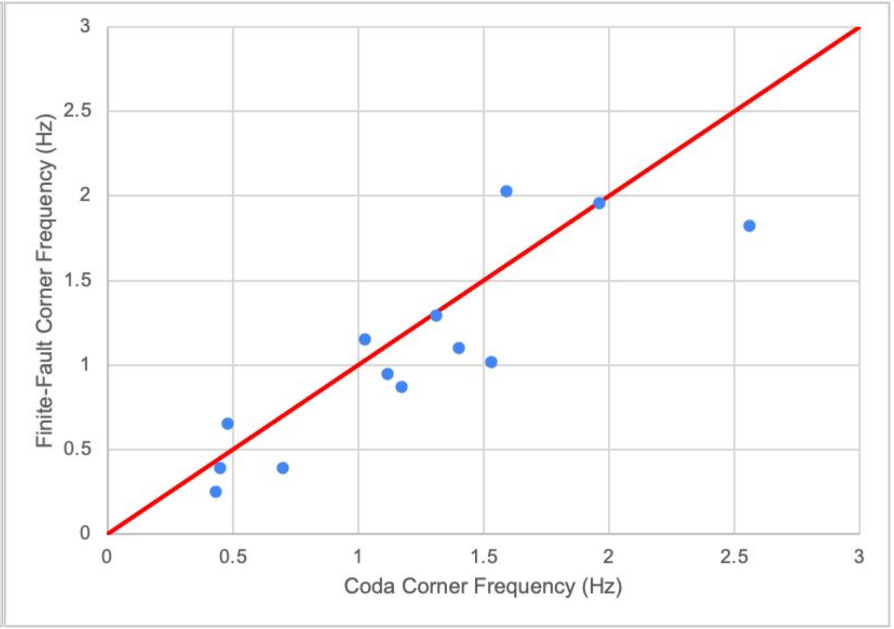
2 Trugman (2022, JGR).

8 selected events

ID	Z	Mag	date-time	CCT fc	CCT Mw	GIT fc	FF fc
38445975	2.3	4.04	‘05-Jul-2019 00:18:01’	1.31	4.07	1.02	1.29
38451079	7.3	4.09	‘05-Jul-2019 12:38:30’	1.53	4.10	1.54	1.02
38471103	7.7	3.30	‘07-Jul-2019 03:23:26’	1.96	3.32	3.43	
38483215	7.7	3.13	‘08-Jul-2019 05:02:10’	3.41	3.02	4.29	
38450263	7.2	5.36	‘05-Jul-2019 11:07:53’	0.45	5.37	0.27	0.39
38538991	2.7	4.13	‘11-Jul-2019 23:45:18’	1.15	4.13	1.25	0.87
38489543	2.8	2.50	‘08-Jul-2019 17:30:03’	N/A			
38496551	10.1	2.57	‘09-Jul-2019 05:17:45’	5.31	2.55	10.18	

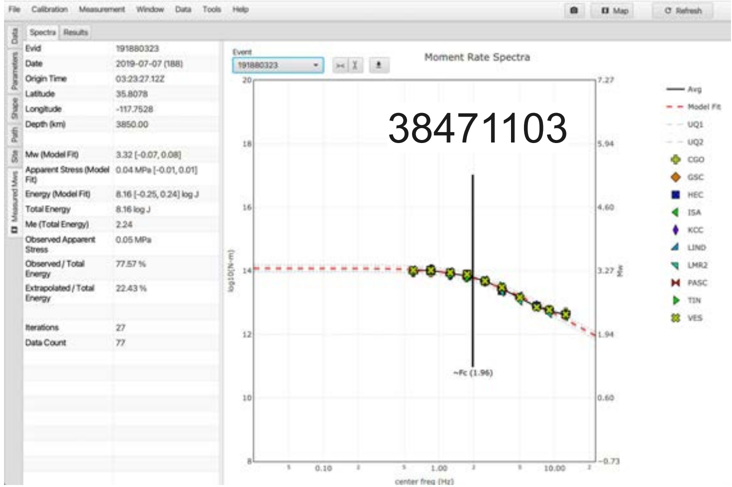
Comparison with Finite Fault Inversion (Dreger)

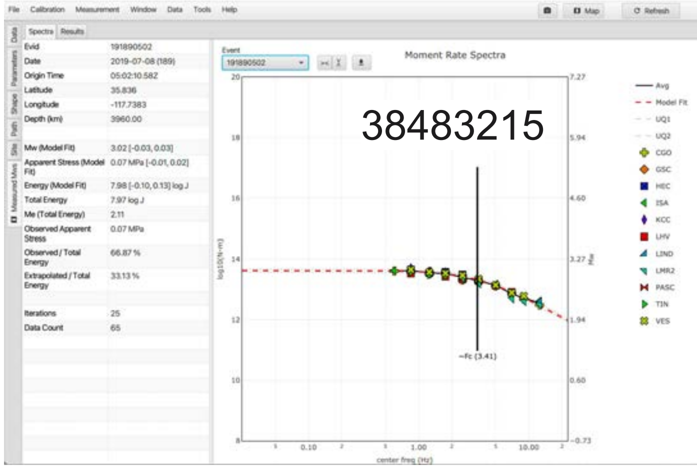


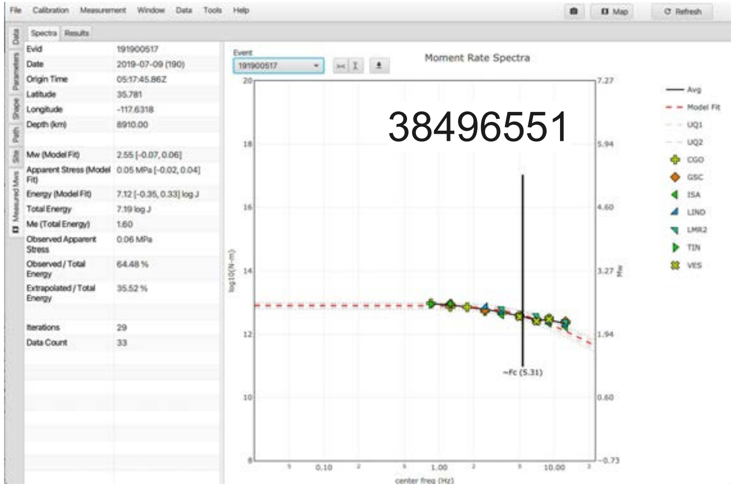


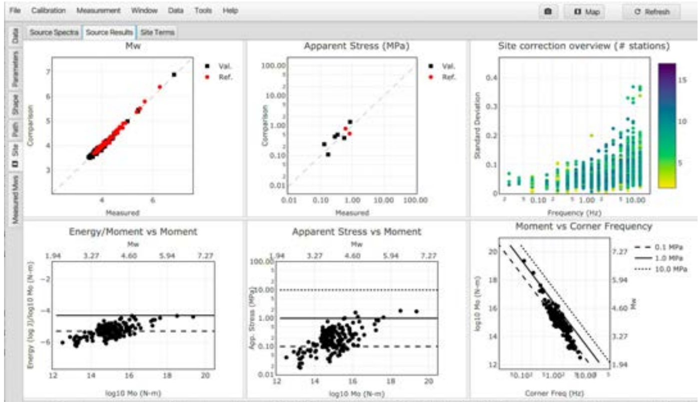
CCT and finite fault estimates of apparent stress and corner frequency for 13 moderate sized events (3.27<Mw<5.53) are in rough agreement. These results are preliminary and outliers will be investigated as will the assumption on *mu*.

CCT *Mw* 2’s and 3’s



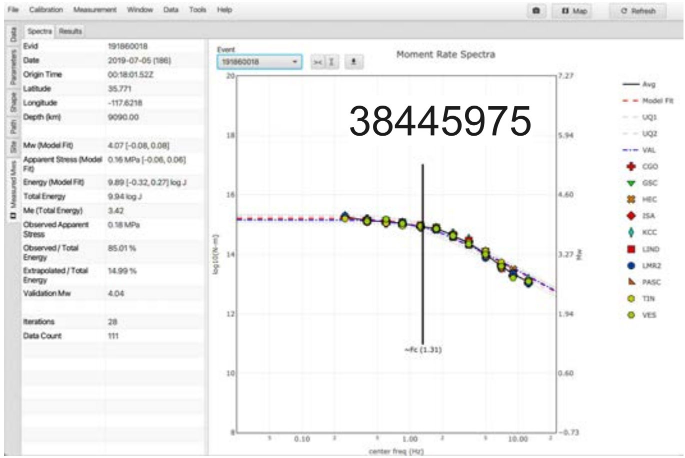


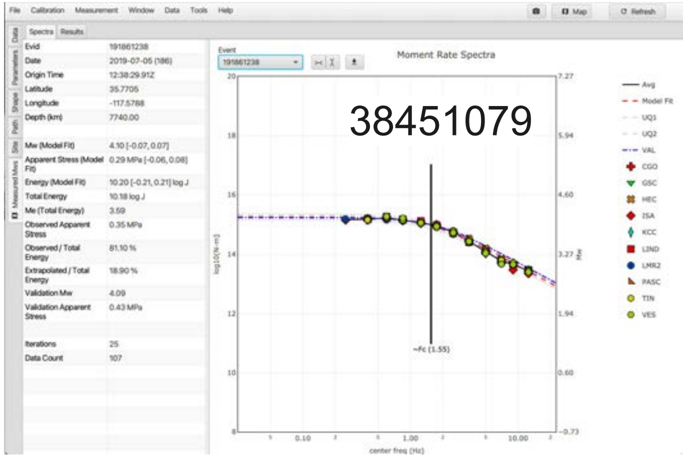


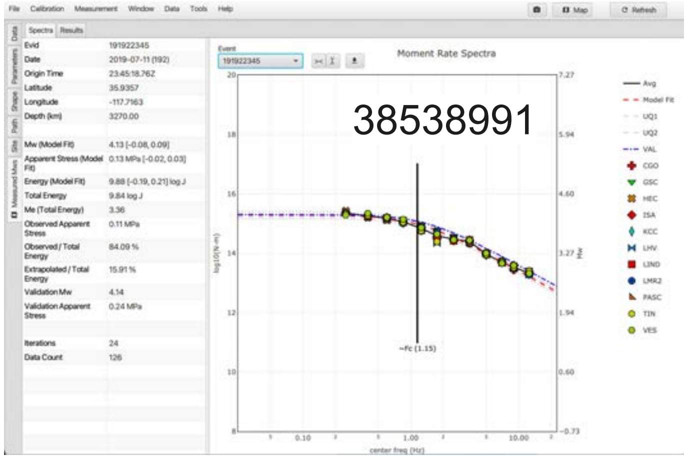


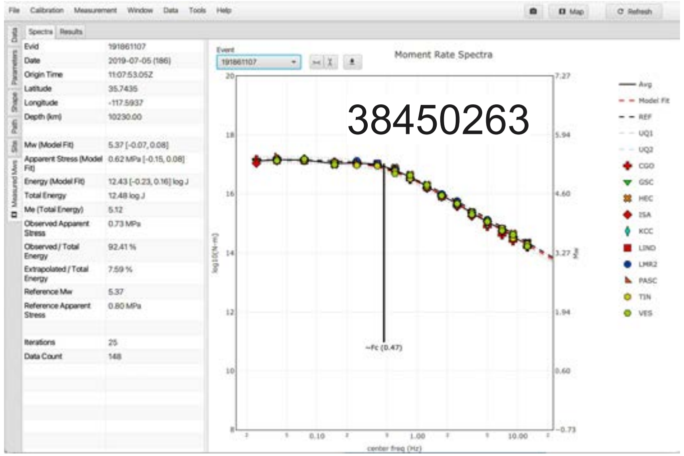
Evid	Date	Mw	Me	ObsTotalEnergy	Obs/TotalObs	ObsAppStress	App.Stress (MPa)	Ref Mw	Ref Stress	Fc (Hz)
210170249	2021-01-17T0...	4.0457	3.5869	10.1804	0.8188	0.3464	0.3082	4.02	0.00	1.6949
191882115	2019-07-07T2...	3.8795	2.9033	9.155	0.8526	0.0582	0.0546			1.1528
201762112	2020-06-24T2...	3.6087	2.8161	9.0242	0.7923	0.1145	0.1014			1.935

CCT *Mw* 4+


Moment Rate Spectra
38445975
Evid 191860018
Date 2019-07-05 (186)
Origin Time 00:18:01.52Z
Latitude 35.771
Longitude -117.6218
Depth (km) 9090.00
Mw (Model Fit) 4.07 [-0.08, 0.08]
Apparent Stress (Model Fit) 0.16 MPa [-0.06, 0.06]
Energy (Model Fit) 9.89 [-0.32, 0.27] log J
Total Energy 9.94 log J
Me (Total Energy) 3.42
Observed Apparent Stress 0.18 MPa
Observed / Total Energy 85.01 %
Extrapolated / Total Energy 14.99 %
Validation Mw 4.04
Iterations 28
Data Count 111
~Fc (1.31)
center freq (Hz)


Moment Rate Spectra
38451079
Evid 191861238
Date 2019-07-05 (186)
Origin Time 12:38:29.91Z
Latitude 35.7705
Longitude -117.5788
Depth (km) 7740.00
Mw (Model Fit) 4.10 [-0.07, 0.07]
Apparent Stress (Model Fit) 0.29 MPa [-0.06, 0.08]
Energy (Model Fit) 10.20 [-0.21, 0.21] log J
Total Energy 10.18 log J
Me (Total Energy) 3.59
Observed Apparent Stress 0.35 MPa
Observed / Total Energy 81.10 %
Extrapolated / Total Energy 18.90 %
Validation Mw 4.09
Validation Apparent Stress 0.43 MPa
Iterations 25
Data Count 107
~Fc (1.55)
center freq (Hz)


Moment Rate Spectra
38538991
Evid 191922345
Date 2019-07-11 (192)
Origin Time 23:45:18.76Z
Latitude 35.9357
Longitude -117.7163
Depth (km) 3270.00
Mw (Model Fit) 4.13 [-0.08, 0.09]
Apparent Stress (Model Fit) 0.13 MPa [-0.02, 0.03]
Energy (Model Fit) 9.88 [-0.19, 0.21] log J
Total Energy 9.84 log J
Me (Total Energy) 3.36
Observed Apparent Stress 0.11 MPa
Observed / Total Energy 84.09 %
Extrapolated / Total Energy 15.91 %
Validation Mw 4.14
Validation Apparent Stress 0.24 MPa
Iterations 24
Data Count 126
~Fc (1.15)
center freq (Hz)

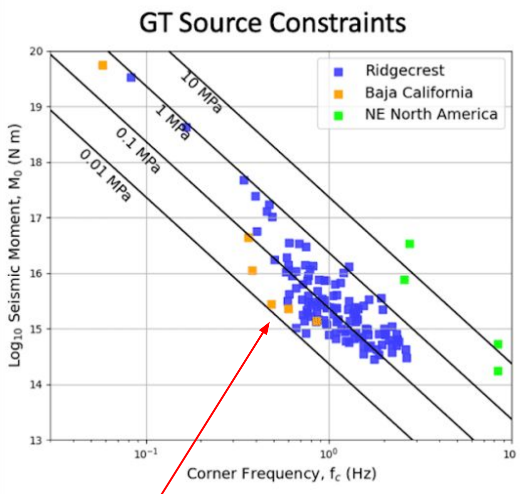

Moment Rate Spectra
38450263
Evid 191861107
Date 2019-07-05 (186)
Origin Time 11:07:53.05Z
Latitude 35.7435
Longitude -117.5937
Depth (km) 10230.00
Mw (Model Fit) 5.37 [-0.07, 0.08]
Apparent Stress (Model Fit) 0.62 MPa [-0.15, 0.08]
Energy (Model Fit) 12.43 [-0.23, 0.16] log J
Total Energy 12.48 log J
Me (Total Energy) 5.12
Observed Apparent Stress 0.73 MPa
Observed / Total Energy 92.41 %
Extrapolated / Total Energy 7.59 %
Reference Mw 5.37
Reference Apparent Stress 0.80 MPa
Iterations 25
Data Count 148
~Fc (0.47)
center freq (Hz)

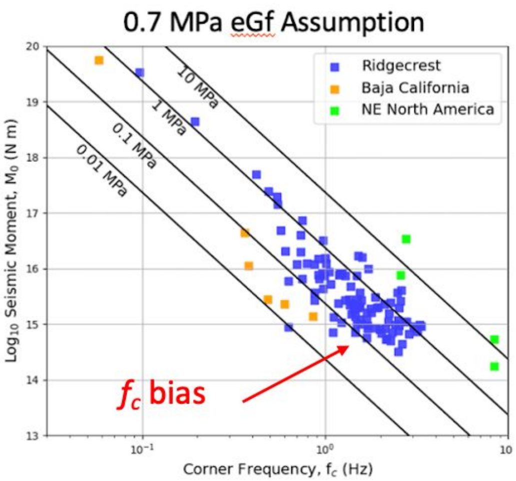
Summary

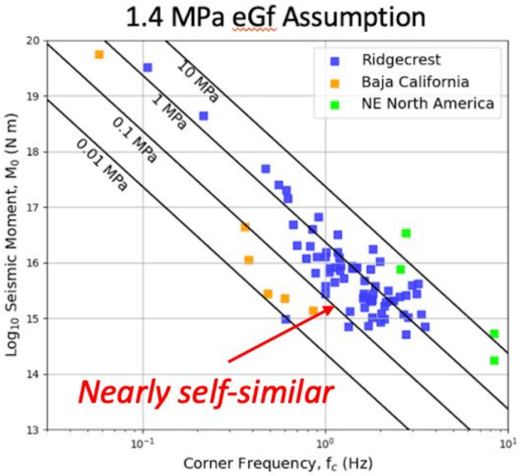
- Varying combinations of GT reference source spectra were tested with no significant changes in the final calibration parameters, source spectra, *Mw*'s and source scaling.
- *Mw*'s match those derived from moment-tensor solutions (Validation *Mw*'s) 3.4<*Mw*<6.9 and simultaneously agree with 6 independent apparent stress estimates.
- We can extend stable *Mw* well below what can be routinely waveform modeled.
- Minimal azimuthal variation observed in single-station source spectra.
- Event 38538991 (*Mw* 4.14) has a spectral hole at ~1.5-2.0-Hz for all stations.
- Event 38445975 has slightly lower apparent stress than event 38451079.
- For common events, apparent stress and corner frequency estimates derived from UC Berkeley's finite fault (3.3<*Mw*<5.53) are in good agreement, as well as those from UCSB (*Mw*>4.0) and GIT results (2.0<*Mw*<6.0).

Source Constraint Affects Site Terms and Scaling

Fixing a handful of *Mw* 4.0 events to high apparent stress as 'reference GT' biases the scaling.







Using independent GT reference events from coda ratios we observe an increase in apparent stress with moment.

To test the ECS approach, we chose six *Mw* ~4.0 'GT reference events' to have apparent stress of 0.7 MPa and 1.4 MPa, which under the *Brune* source shape assumption is roughly equal to a 3 MPa and 6 MPa *Brune* stress drop (center and right figure, respectively). When compared against the calibration that used GT spectral constraints (left), we see a bias at lower magnitudes and an overall increase in apparent stress over the entire magnitude range. (Note: Only the site terms change. Path correction and envelope shape remain the same but cannot match original GT ratios in previous slide.)

EXTRA SLIDES

ID logMo SElogMo fc SEfc stress_drop_vs_3D SEstdr stress_drop_vs_const

38445975 15.3299270379856 0.048093448591591 1.01800708086084 0.0709773196228018 0.701005826965392 0.153084738877273 0.582907428046382

38451079 15.2838751467793 0.0141603841348427 1.53798101398198 0.0340682640793185 1.40095798764162 0.086164369196776 1.80779101987969

38471103 13.9124399875432 0.0156534898192737 3.43279312034761 0.0965513082003814 0.623354726754051 0.0324365772827538 0.854679006011451

38483215 13.6108637499221 0.0128252383736518 4.29091716382966 0.105832422723926 0.607163883877048 0.0458378593156059 0.833555068929524

38450263 17.6119424143883 0.0883602670144013 0.267276416901024 0.0287987412297874 1.56019827783463 0.592304288984253 2.01950294683978

38538991 15.3238473611207 0.0298362312433606 1.25085386492333 0.0561163992243787 1.22449686483017 0.163947443674182 1.06631922849795

38496551 12.8702041635577 0.0100399566274271 10.1845234583118 0.281673992958635 1.47276926322507 0.30875575880591 2.02509992377904

Spectral Ratios - Choice of EGF, Time Window etc.

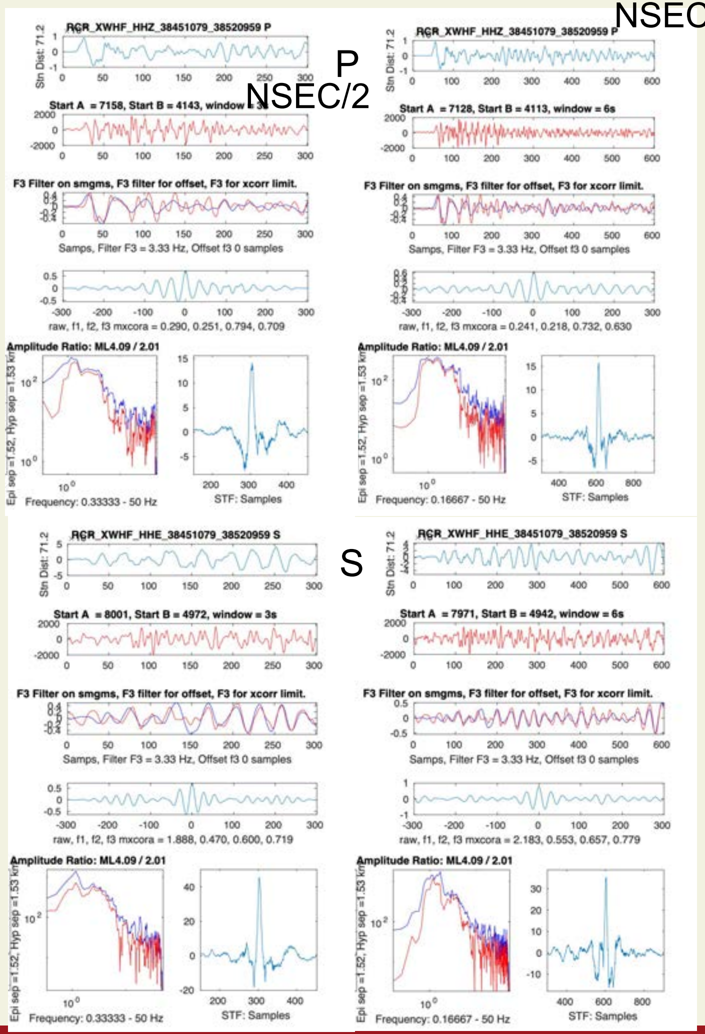
Apply Methods of Abercrombie et al., 2017; 2020 etc. to Ridgecrest Earthquakes

Find all Small events within
2 km epicentral distance
1.2 and 2.5 M units < main
(both ranges iteratively decreased IF >>200 EGFs found)

Define time window NSEC = constant * $M0^{1/3}$
Try 0.5NSEC to get more P waves for close stations

Try various EGF threshold depending on cross correlation and hypocentral depth difference

Rachel Abercrombie
Boston University
rea@bu.edu



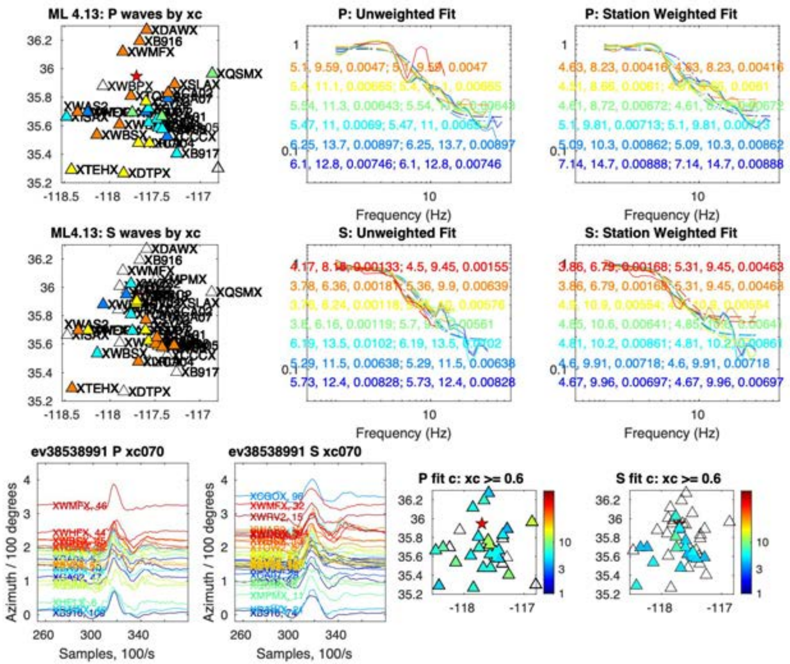
Example EGF Spectral Ratios: 38538991 M4.13

Minimum cross correlation = [0.5 0.5 0.6 0.7 0.7 0.8 0.9]

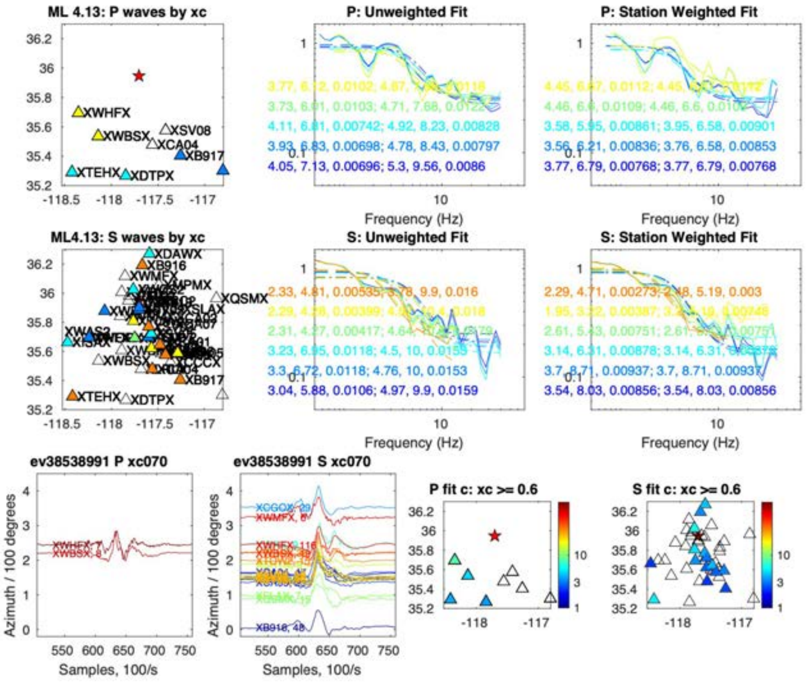
Max depth difference to main = [10 1 10 10 1 10 10]

Rachel Abercrombie

0.5 NSEC = 3.15 s



1 NSEC = 6.3 s



Example EGF Spectral Ratios: 38538991 M4.13

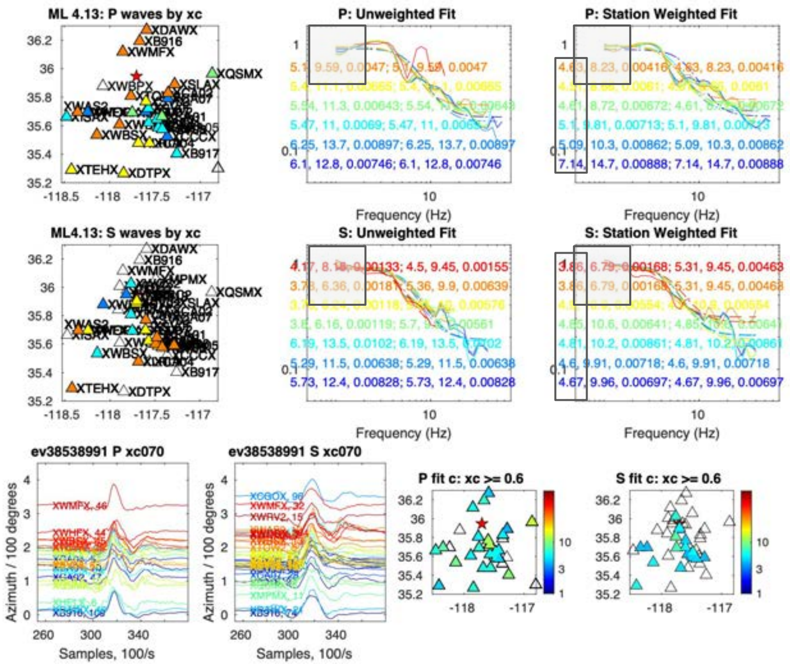
Minimum cross correlation = [0.5 0.5 0.6 0.7 0.7 0.8 0.9]

Max depth difference to main = [10 1 10 10 1 10 10]

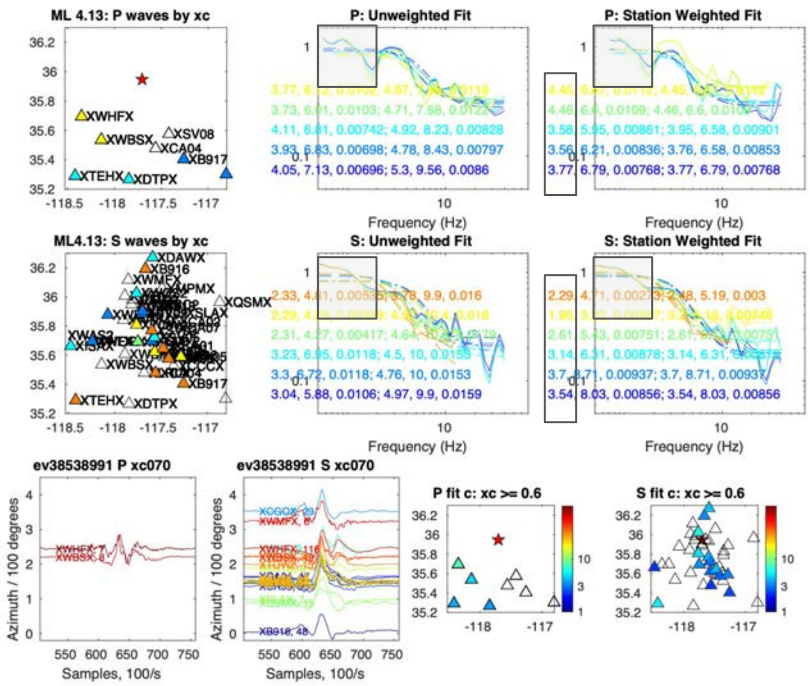
Rachel Abercrombie

fc1, fc2, variance (no constraints)
fc1, fc2, variance (limits on fc2)

0.5 NSEC = 3.15 s



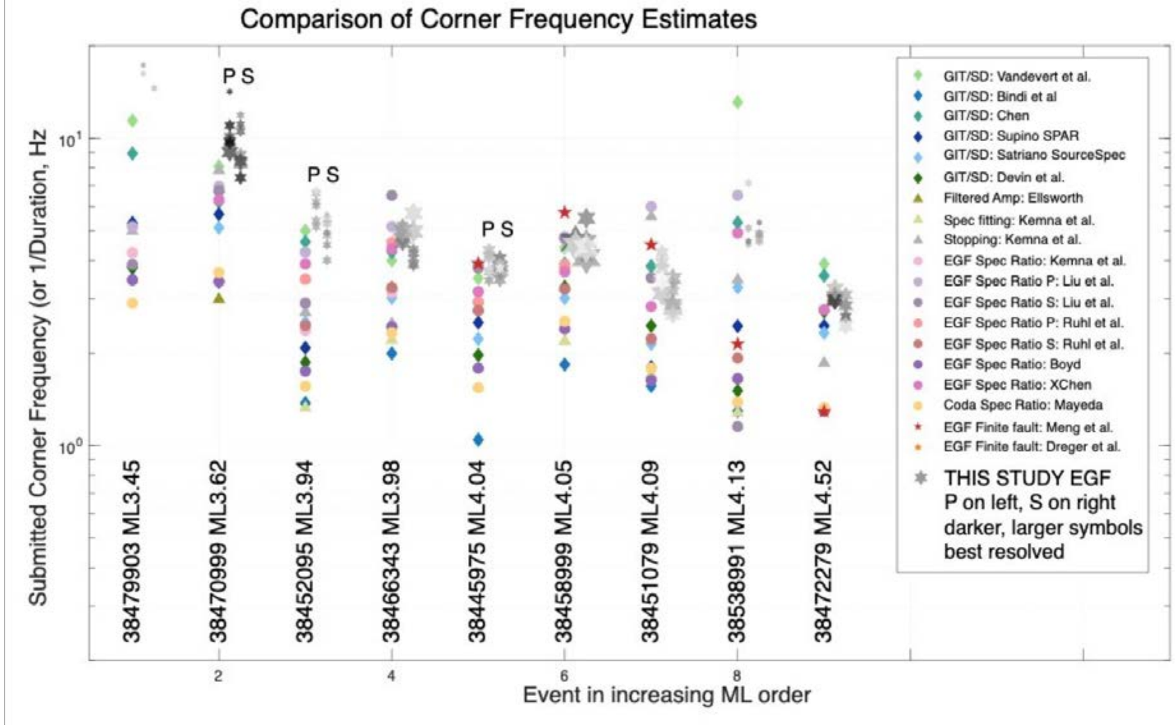
1 NSEC = 6.3 s

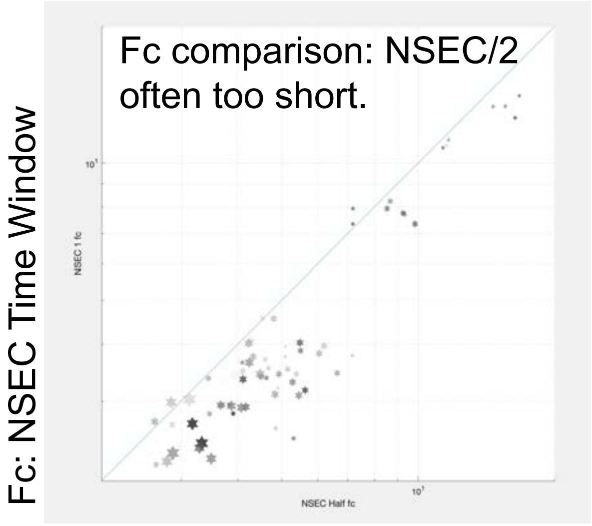


Look for consistency in Different Cross correlations? Time Window affects Frequency Range

Rachel Abercrombie

Comparison of EGF Variation Effects to Other Methods



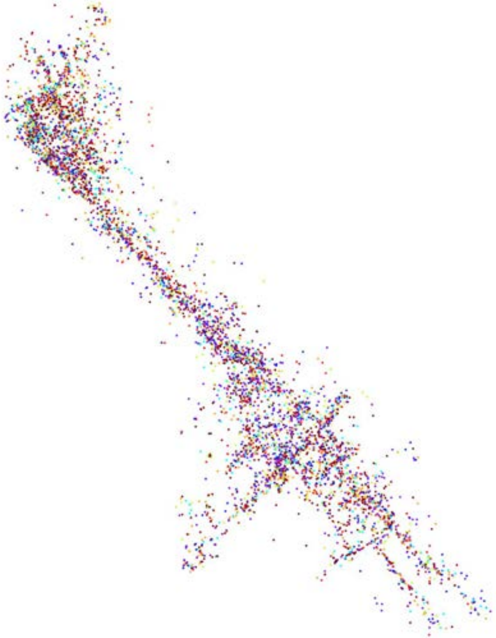


Fc: NSEC/2 Time Window

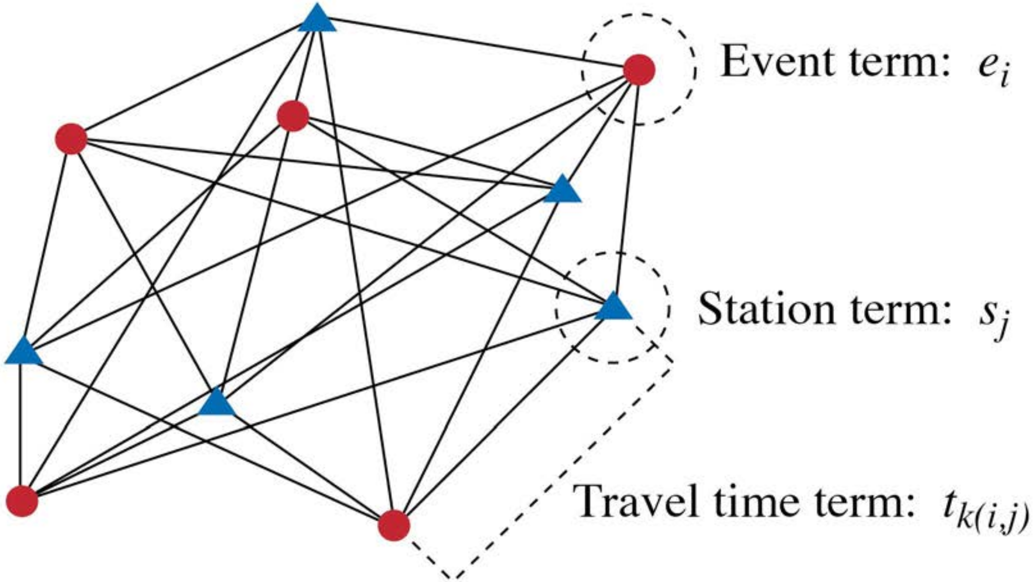
Ridgecrest P and S spectral decomposition comparisons

Peter Shearer, Ian Vandevert & Wenyuan Fan

IGPP/SIO/U.C. San Diego



Spectral decomposition



$$d_{ij} \approx e_i + s_j + t_{k(i,j)} + r_{ij} \text{ (residual)}$$

Observed spectrum

Source spectrum

Receiver response

Travel-time dependent term to account for Q

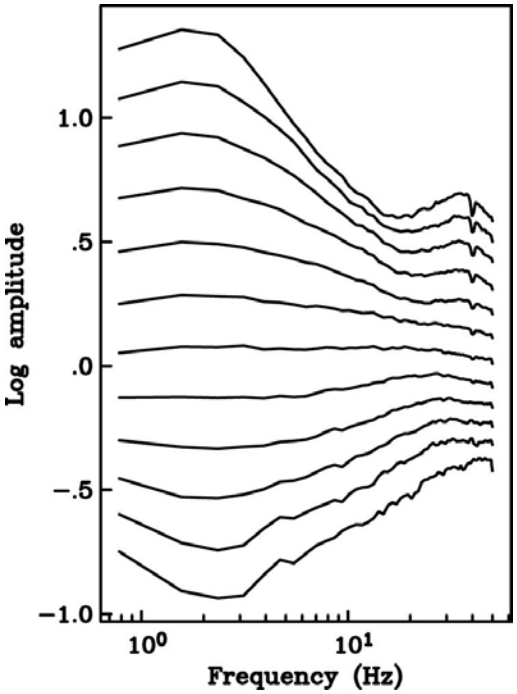
Good for uniform processing of large data sets.

Variations of this approach used by *Shearer, Allmann, Chen, Trugman, Oth*, and others.

Completely empirical—a great advantage but one that has its limitations

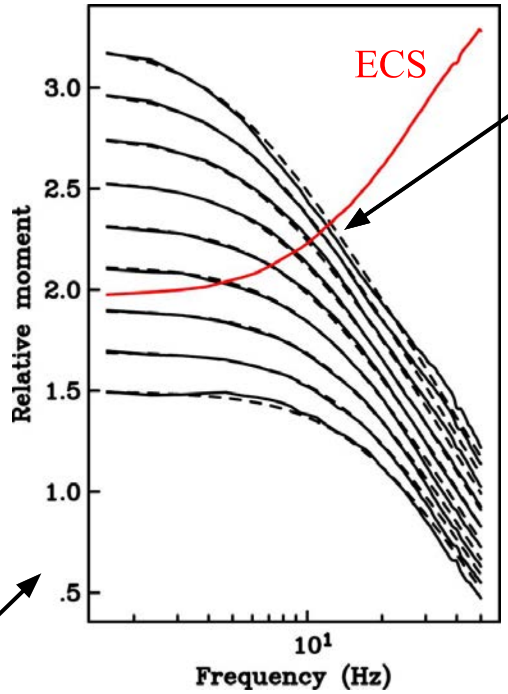
Old approach: Solve for global ECS function and *fc* model that best fit entire data set

Raw source terms



Solve for Δσ model and Empirical Correction Spectrum (ECS)

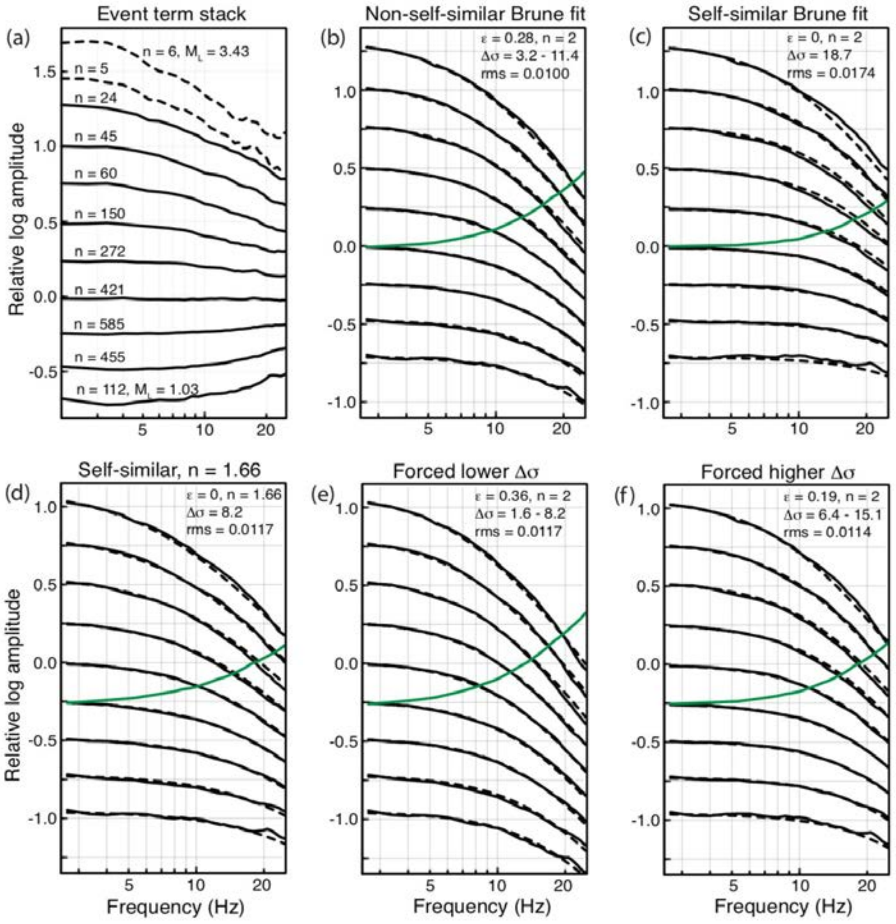
ECS corrected



Dashed lines show model predictions

Source spectra binned by relative moment

Results indicate method has too many free parameters!



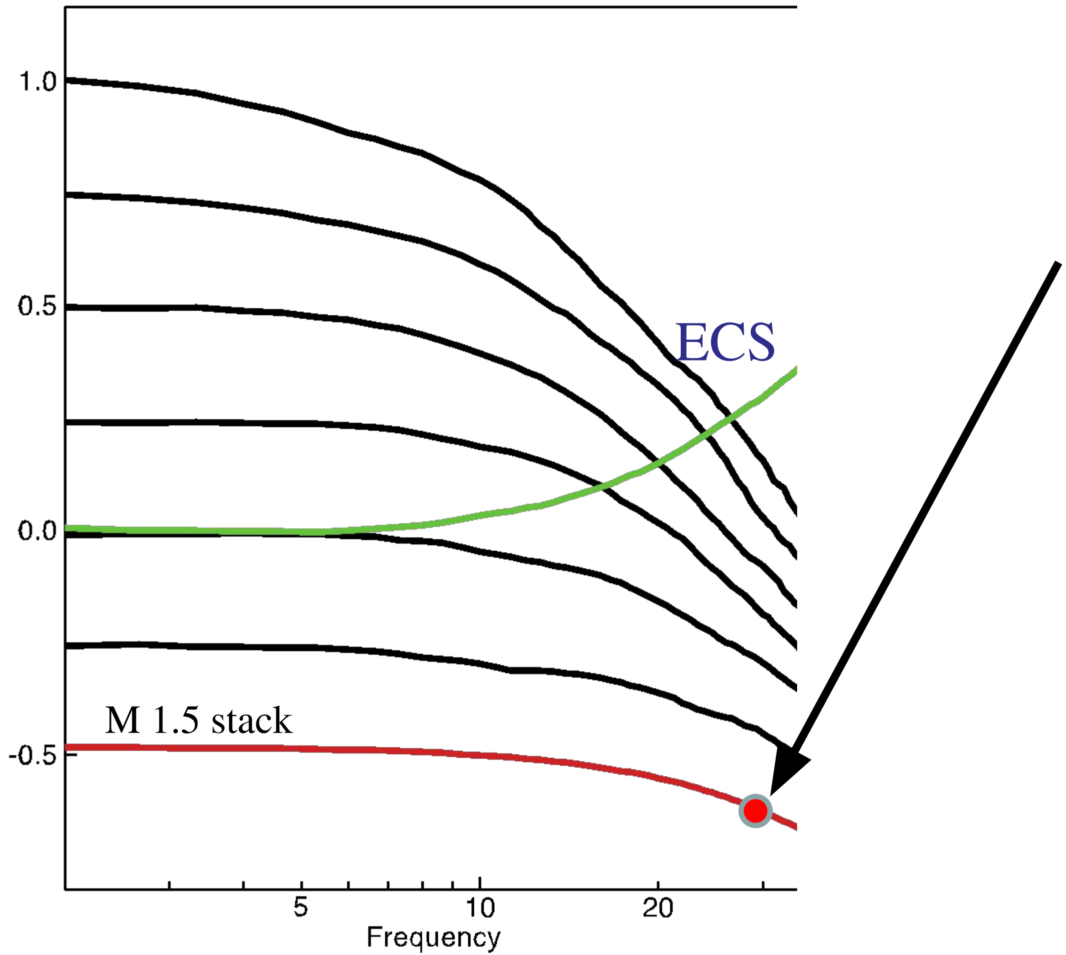
from *Shearer, Abercrombie, Trugman & Wang* (2020)

For Landers cluster, **many different models can fit the data, given tradeoffs among the model parameters and the global EGF function**.

Thus, we cannot be sure of the absolute level of stress drop, the high-frequency fall off rate, or non-self-similar scaling factors. These issues require **independent constraints on the EGF function.**

However, **relative differences in stress drop among events in the same cluster are well-resolved**, when estimated using the same EGF function.

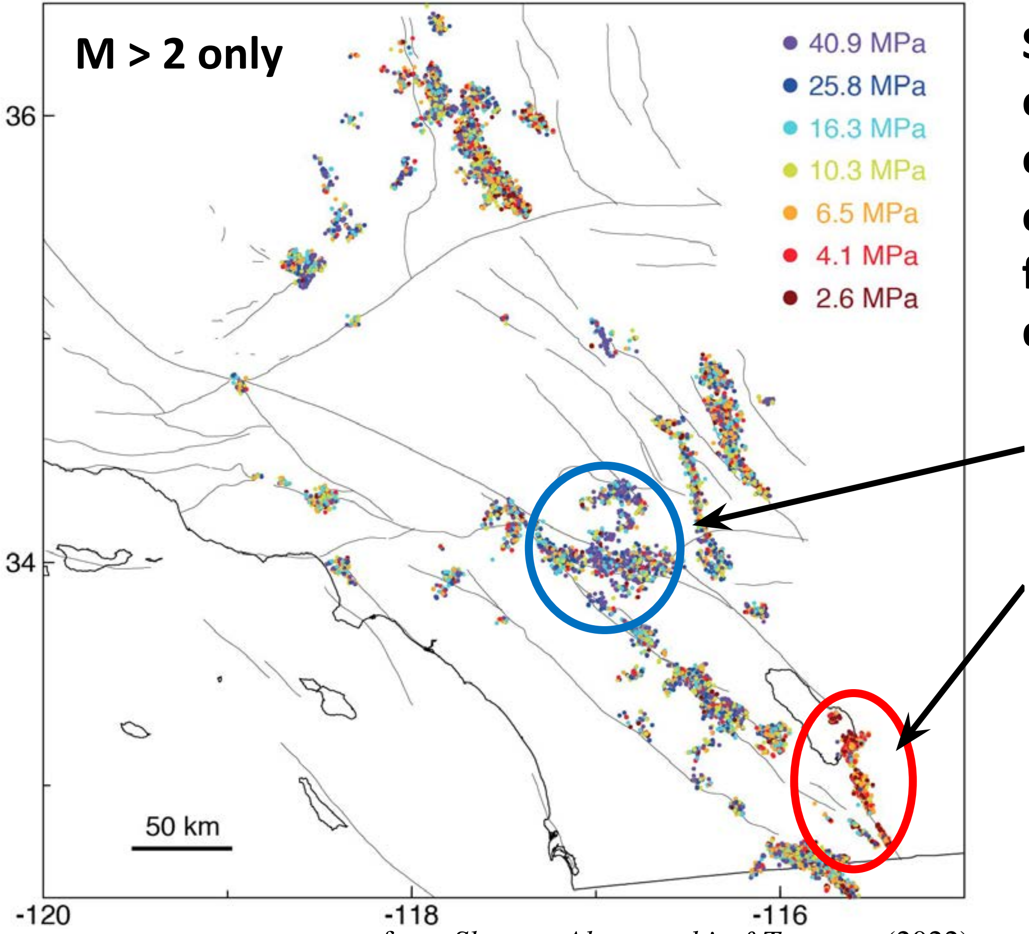
New approach: Locally fix small earthquake average corner frequency



Force the Brune corner frequency (fc) of nearby M 1.5 earthquakes to 30 Hz in estimating the ECS for each target event.

This directly determines the ECS at each location and ensures that any spectral differences seen in M > 1.5 earthquakes are caused by source variations rather than inaccurate path corrections.

Our results for southern California: robust spatial variations

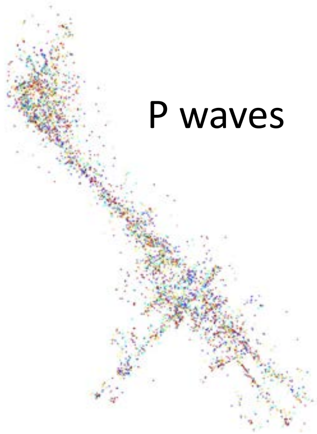


from *Shearer, Abercrombie &Trugman* (2022)

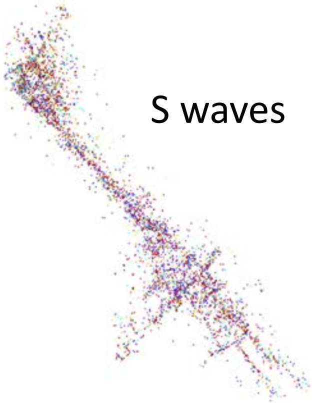
Stress drop estimates for 28,685 M 2 to 4 earthquakes (1996–2019). Each earthquake has at least 10 M ≲ 1.6 calibration events (assumed to have Brune fc = 30 Hz) within 5 km in horizontal distance and 2 km in depth.

These lateral variations in average stress drop must be real because they are derived from the relative behavior of M > 2 quakes with respect to M 1.5 quakes in each local region, i.e., any propagation path differences are removed.

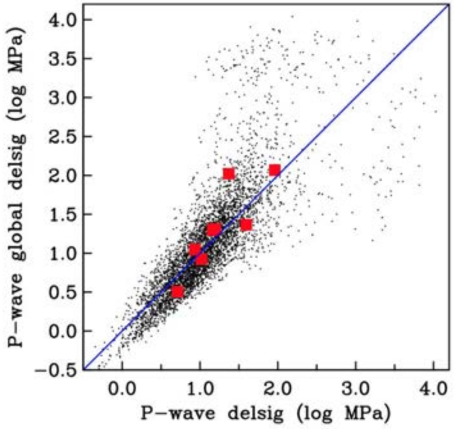
Applications to Ridgecrest test dataset

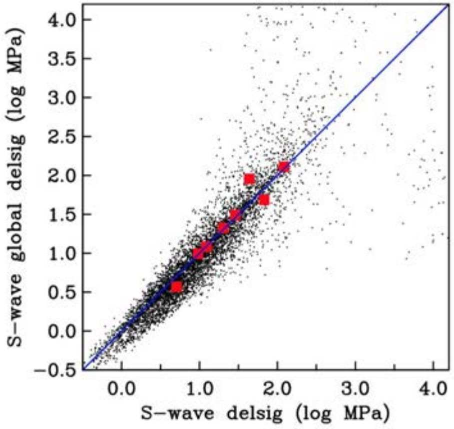


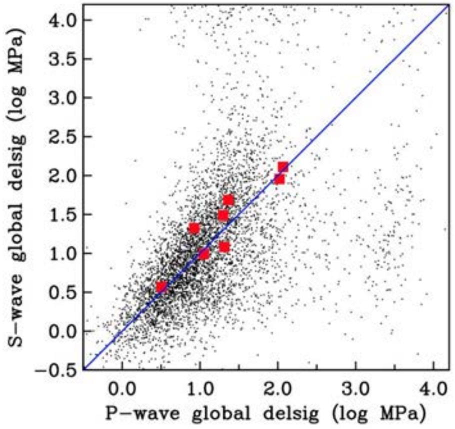
P waves

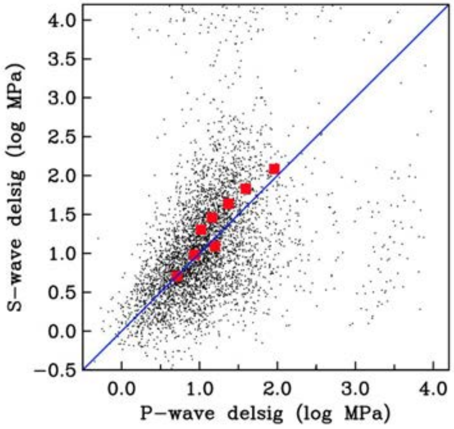


S waves

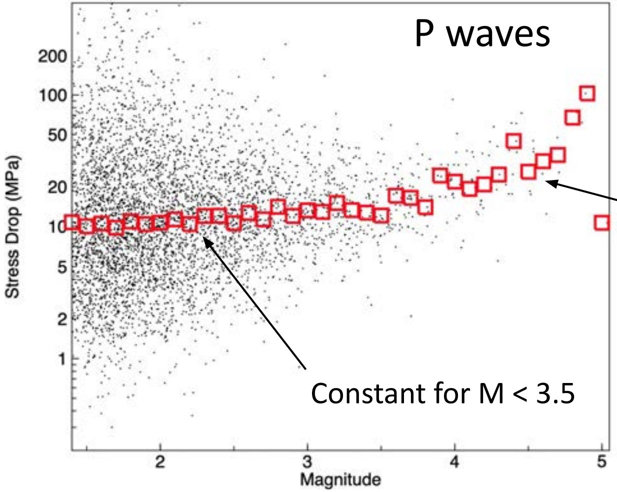




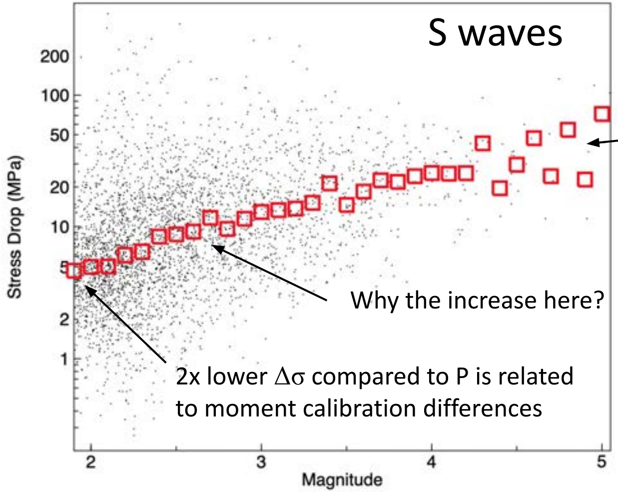




Median stress drop vs. magnitude shows increase—is it real?



Increase at M > 3.5 is likely mostly artifact caused by unresolved low-frequency part of spectrum and/or HF falloff rate < 2

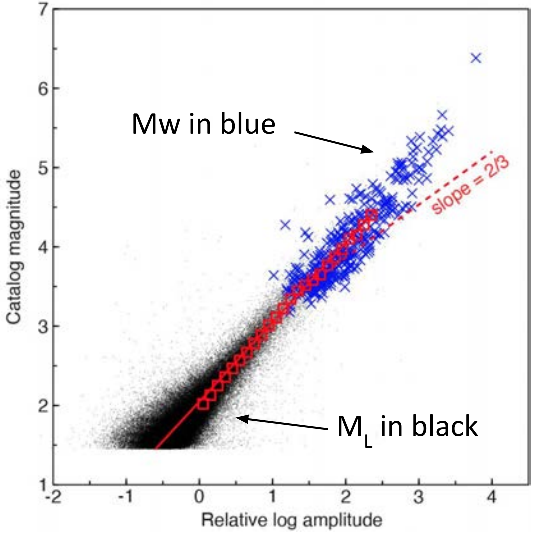


Somewhat more stable results for M > 4.5 quakes than P results

Resolving the low-frequency (< 1 Hz) part of the spectrum is key for getting reliable results for larger (M > 4) quakes.

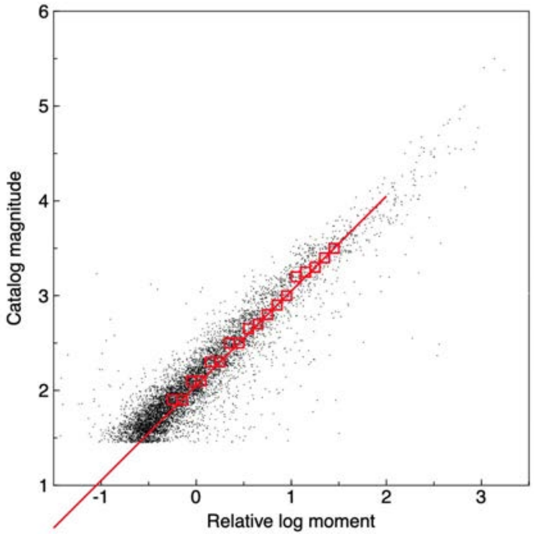
Problem: relative moments vs catalog magnitude do not show expected change in slope as M_L changes to Mw for M > 3.5

SCSN P wave analysis

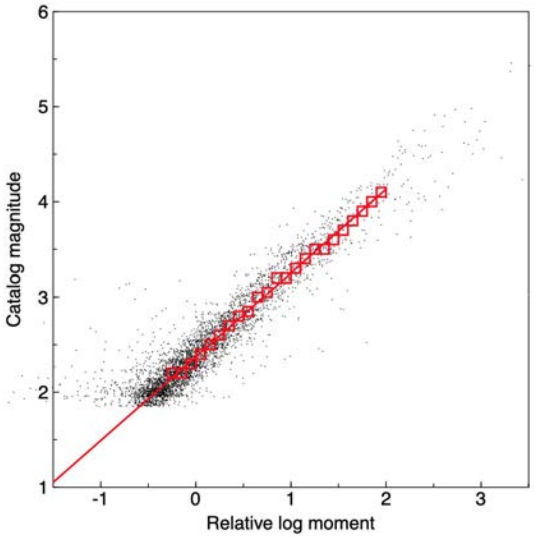


from *Shearer, Abercrombie &Trugman* (2022)

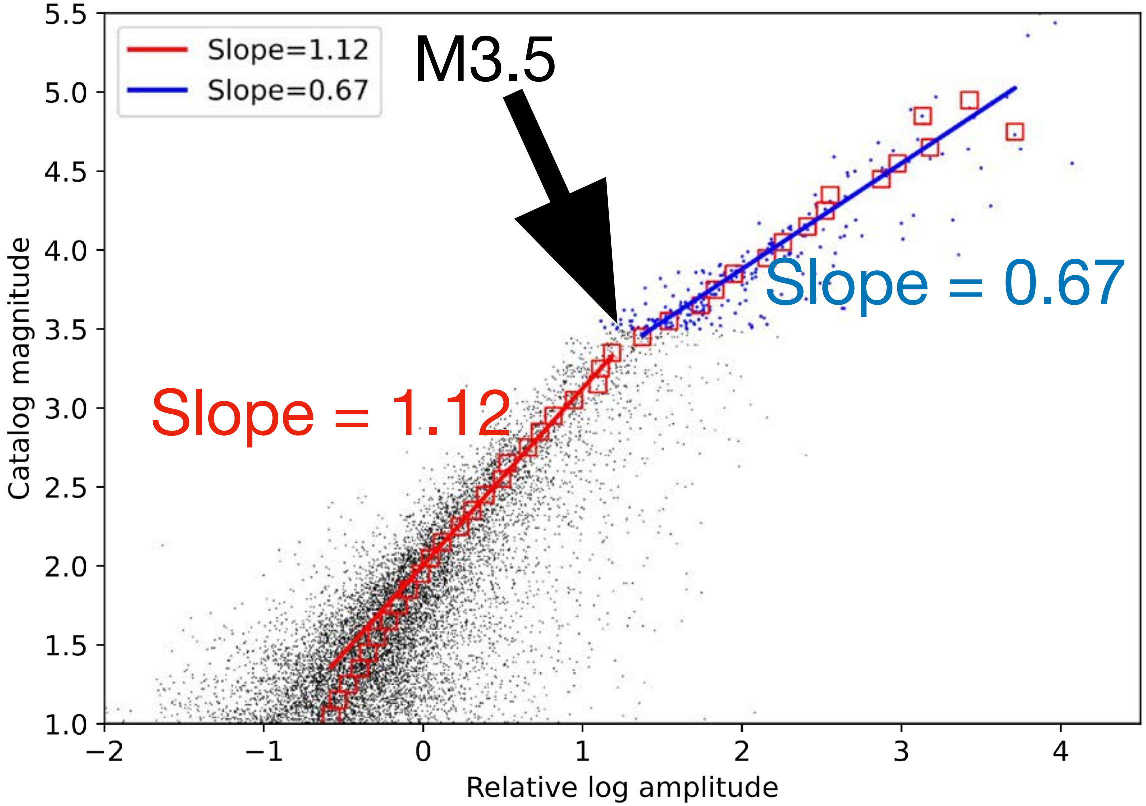
Ridgecrest P wave analysis



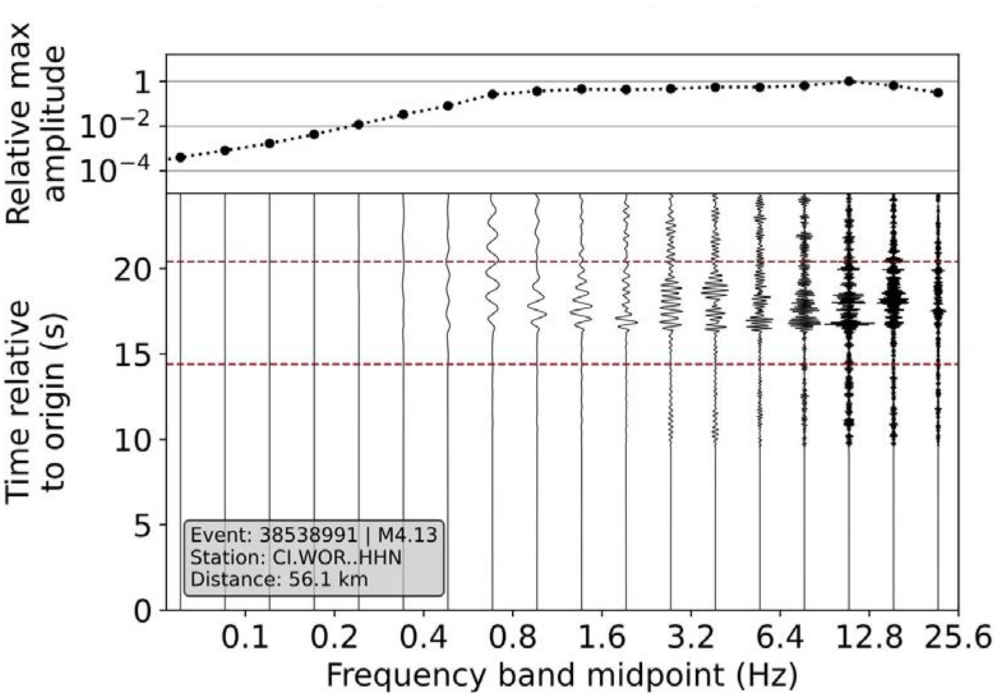
Ridgecrest S wave analysis



Ridgecrest S-wave amplitude decomposition and comparison to S-wave spectral decomposition

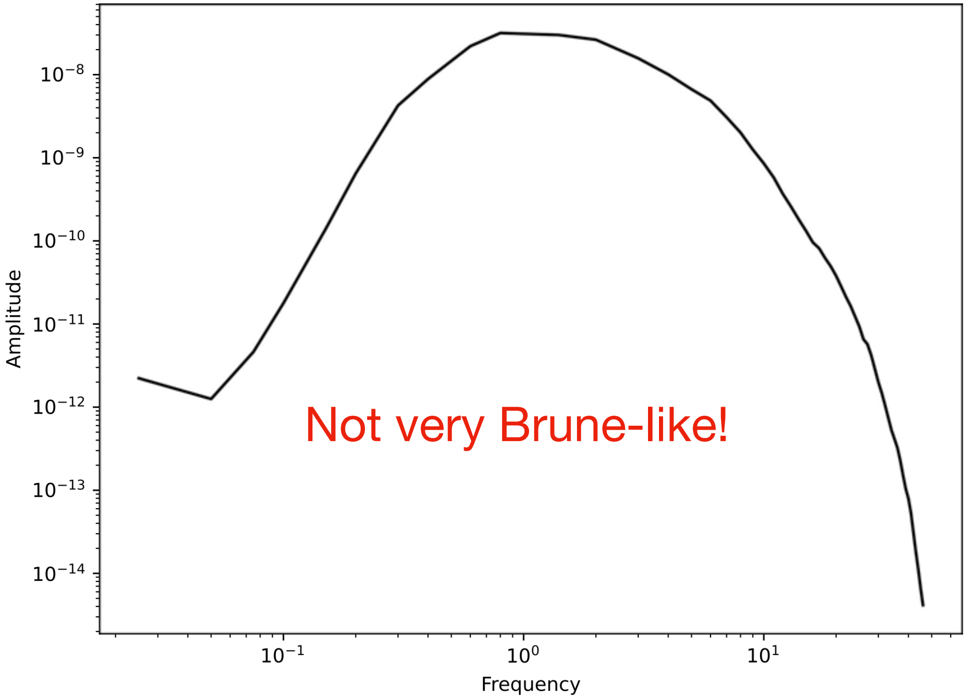


New method: S-wave amplitude decomposition in the time domain



1. Estimate S-wave arrival
2. Filter entire trace at different frequency bands, measure peak amplitude
3. Assemble observed spectrum
4. Invert to get event terms

Example event term (S-wave displacement)



Empirical correction spectrum (ECS)

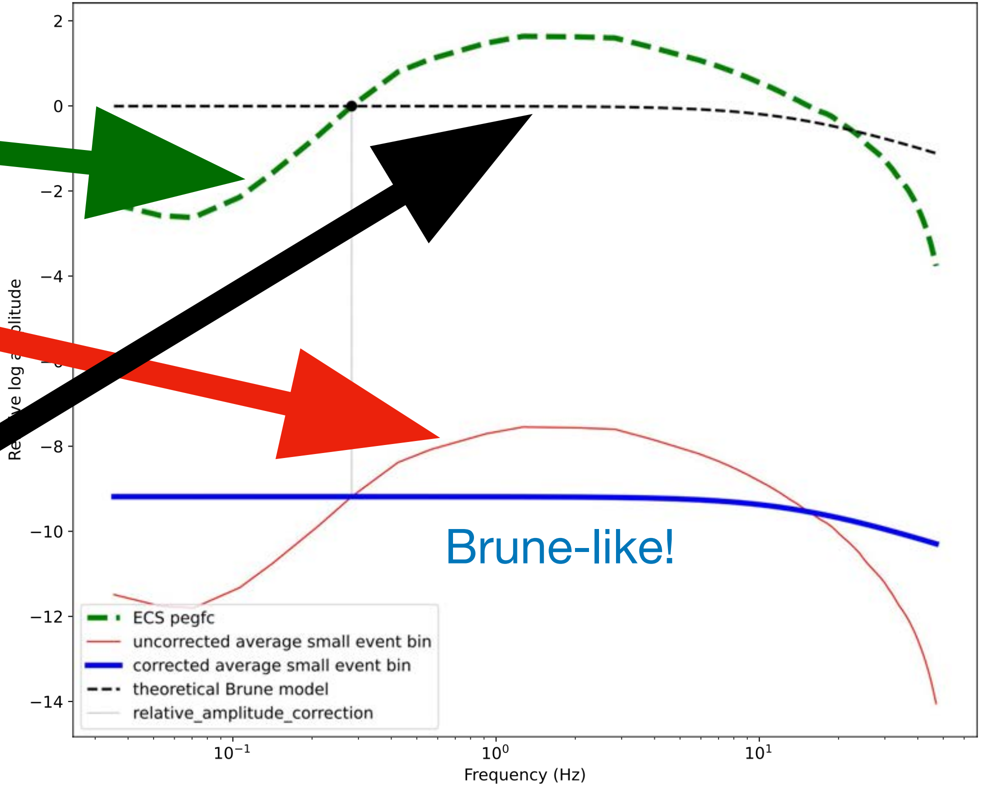
ECS

=

observed spectrum

-

Brune

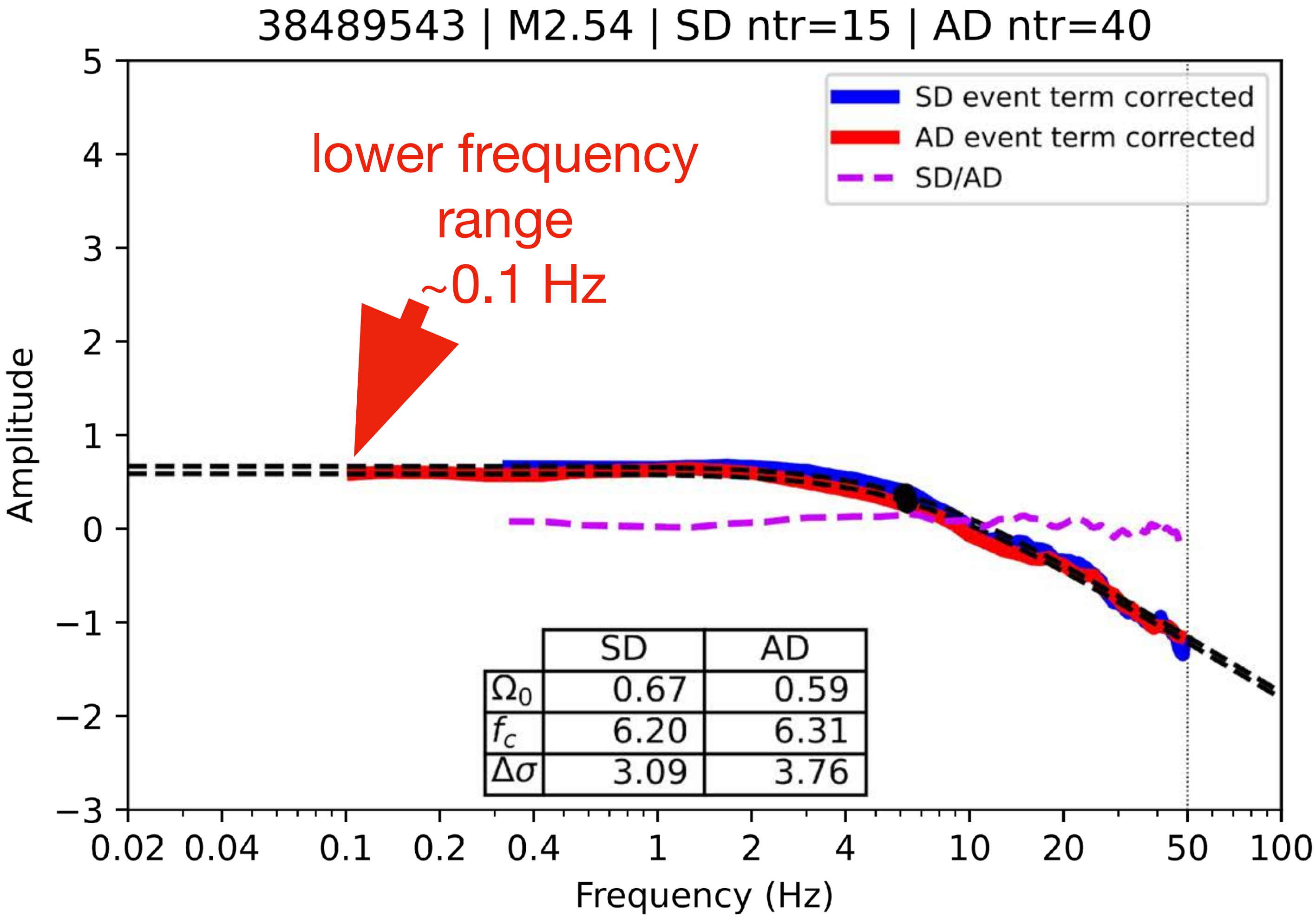


solution: force it to be Brune!

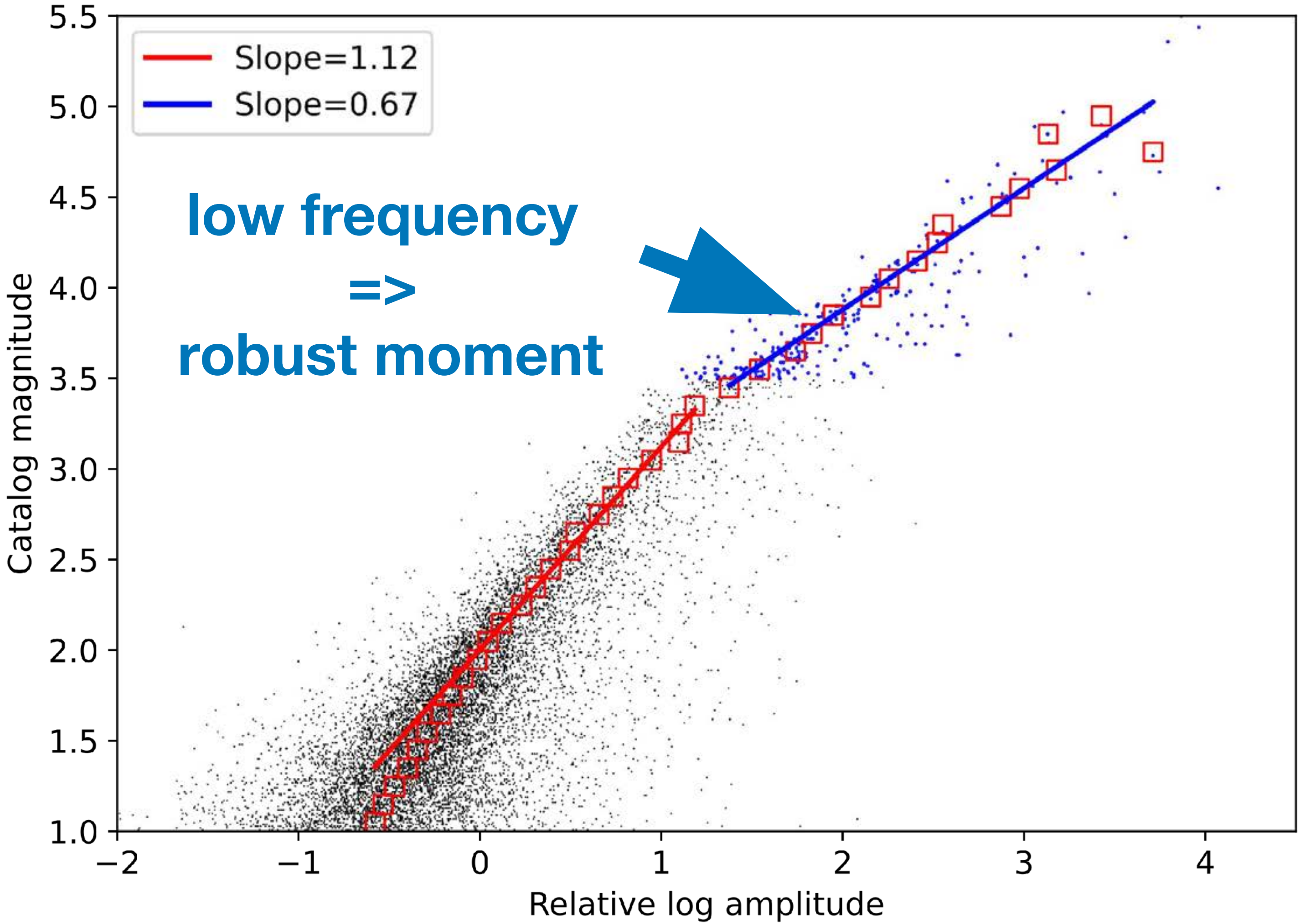
(for M1.9-2.1 earthquakes fix a

corner frequency of 14 Hz)

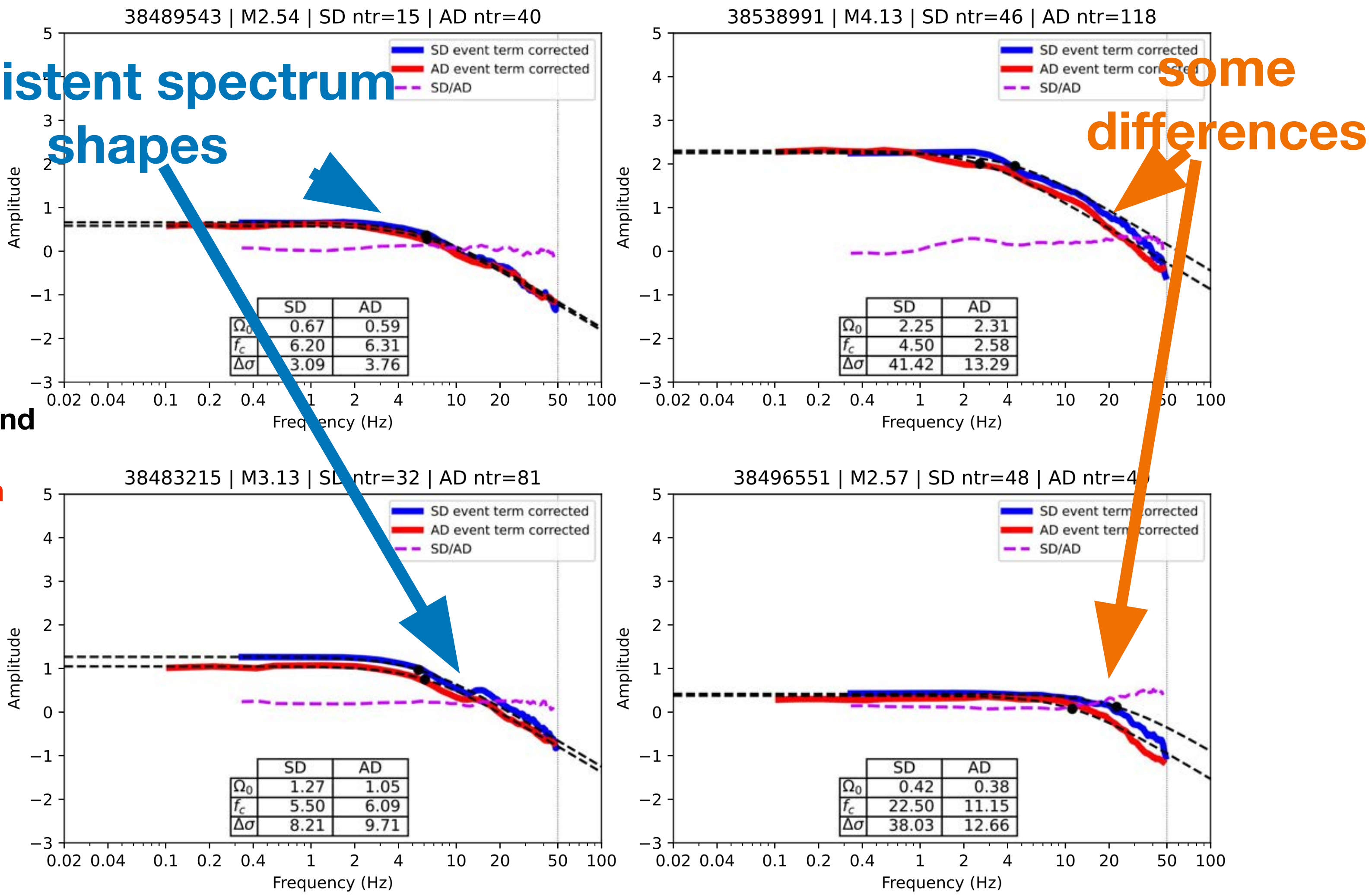
Comparison of spectral decomposition to amplitude decomposition



	SD	AD
Ω_0	0.67	0.59
f_c	6.20	6.31
$\Delta\sigma$	3.09	3.76

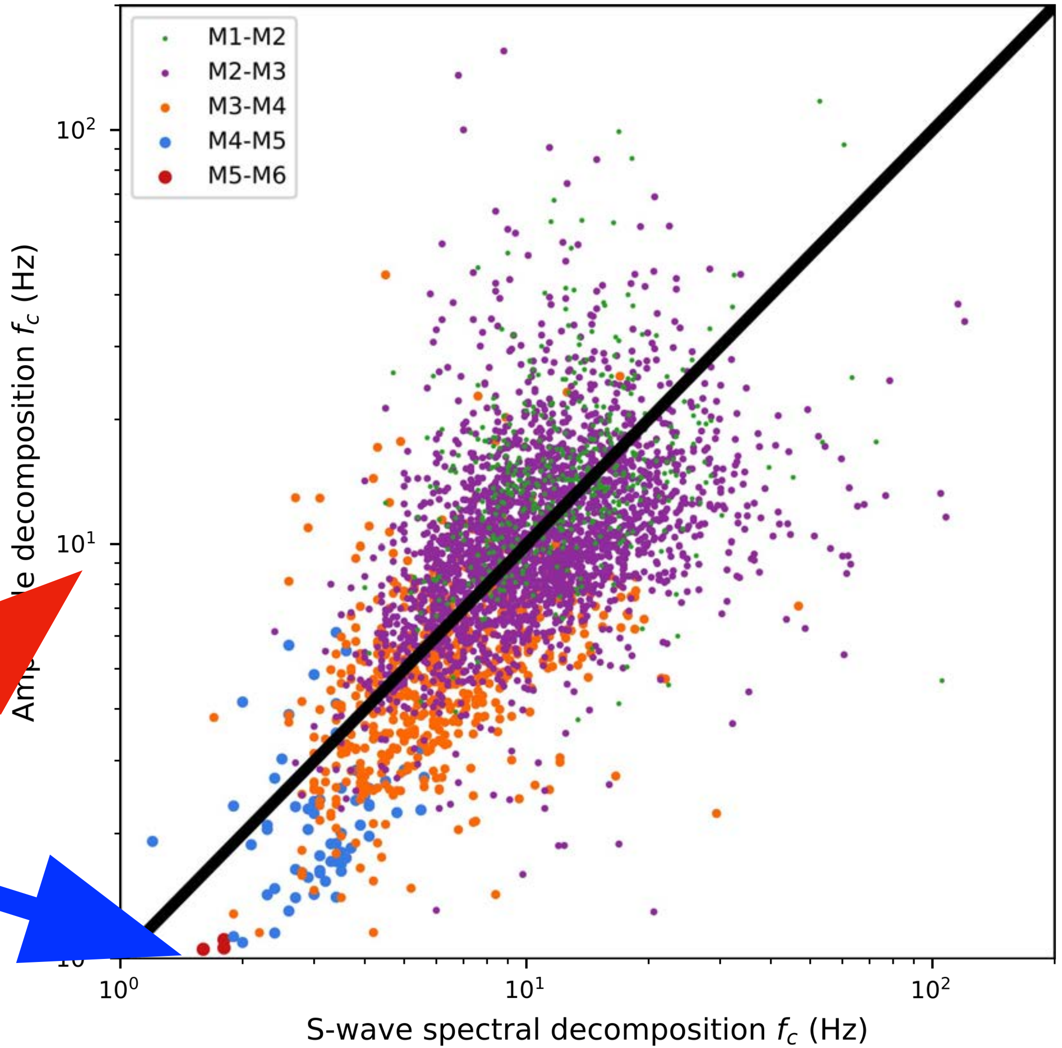

Slope=1.12
Slope=0.67
low frequency
=>
robust moment
Catalog magnitude
Relative log amplitude
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
−2
−1
0
1
2
3
4

spectrum decomposition and **amplitude decomposition**



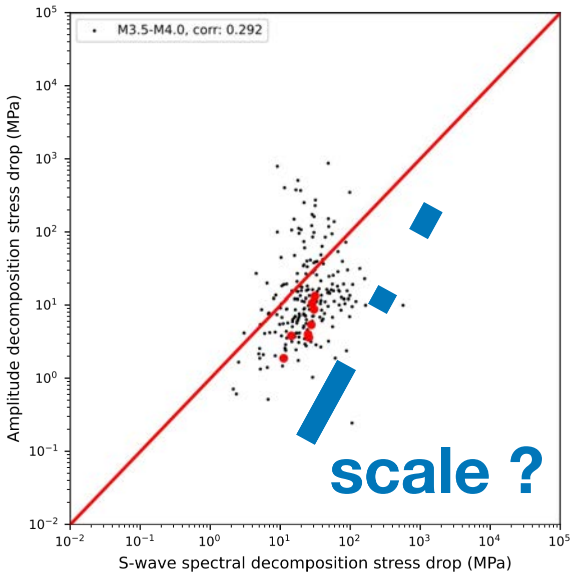
Corner frequency estimates from the two methods **correlate** with each other

amplitude decomposition **and** **spectrum decomposition**

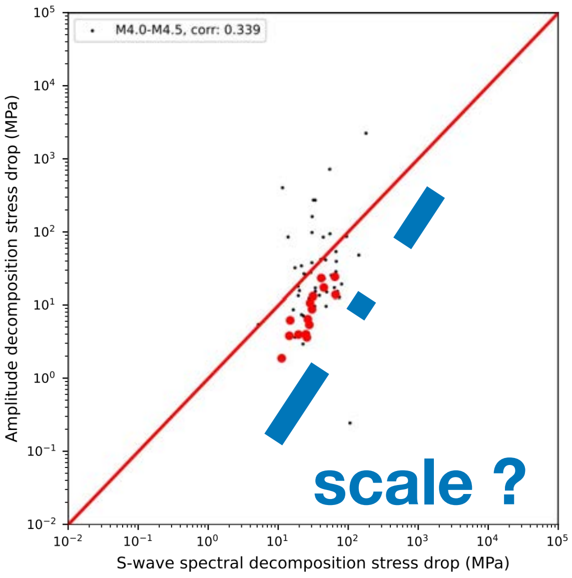


stress drop estimates from the two methods **correlate** with each other (M>3.5)

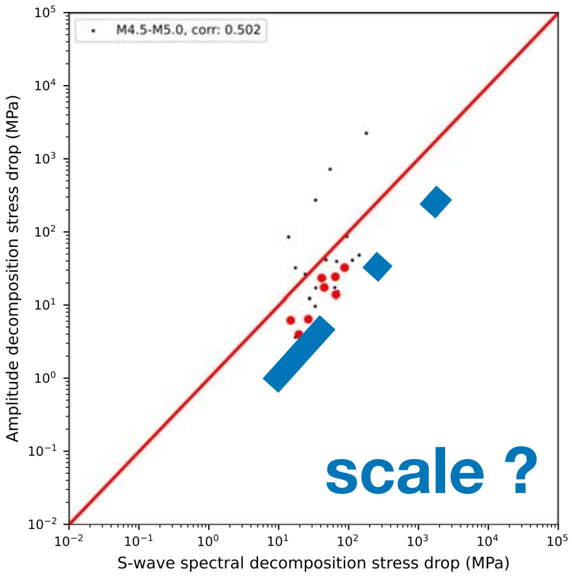
M3.5-4



M4-4.5

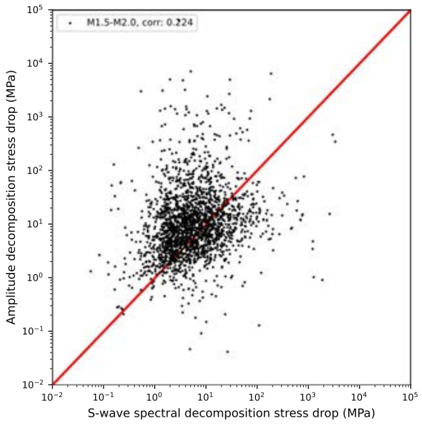


M4.5-5

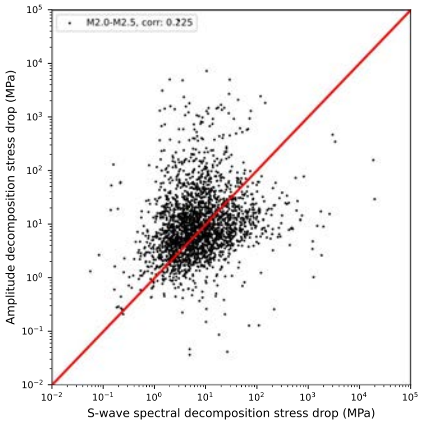


stress drop estimates from the two methods **show scatters for** M<3.5 ??

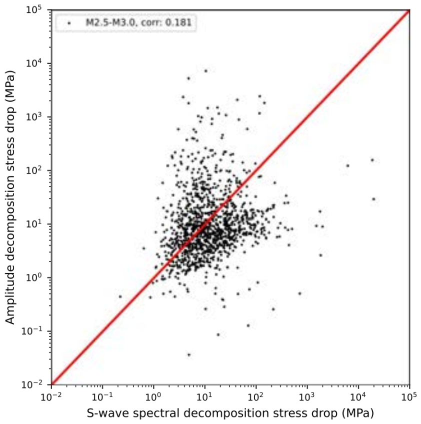
M1.5-2



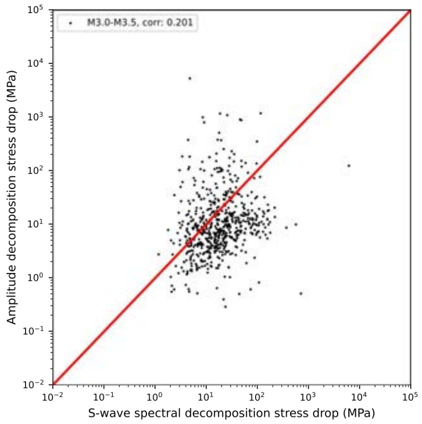
M2-2.5

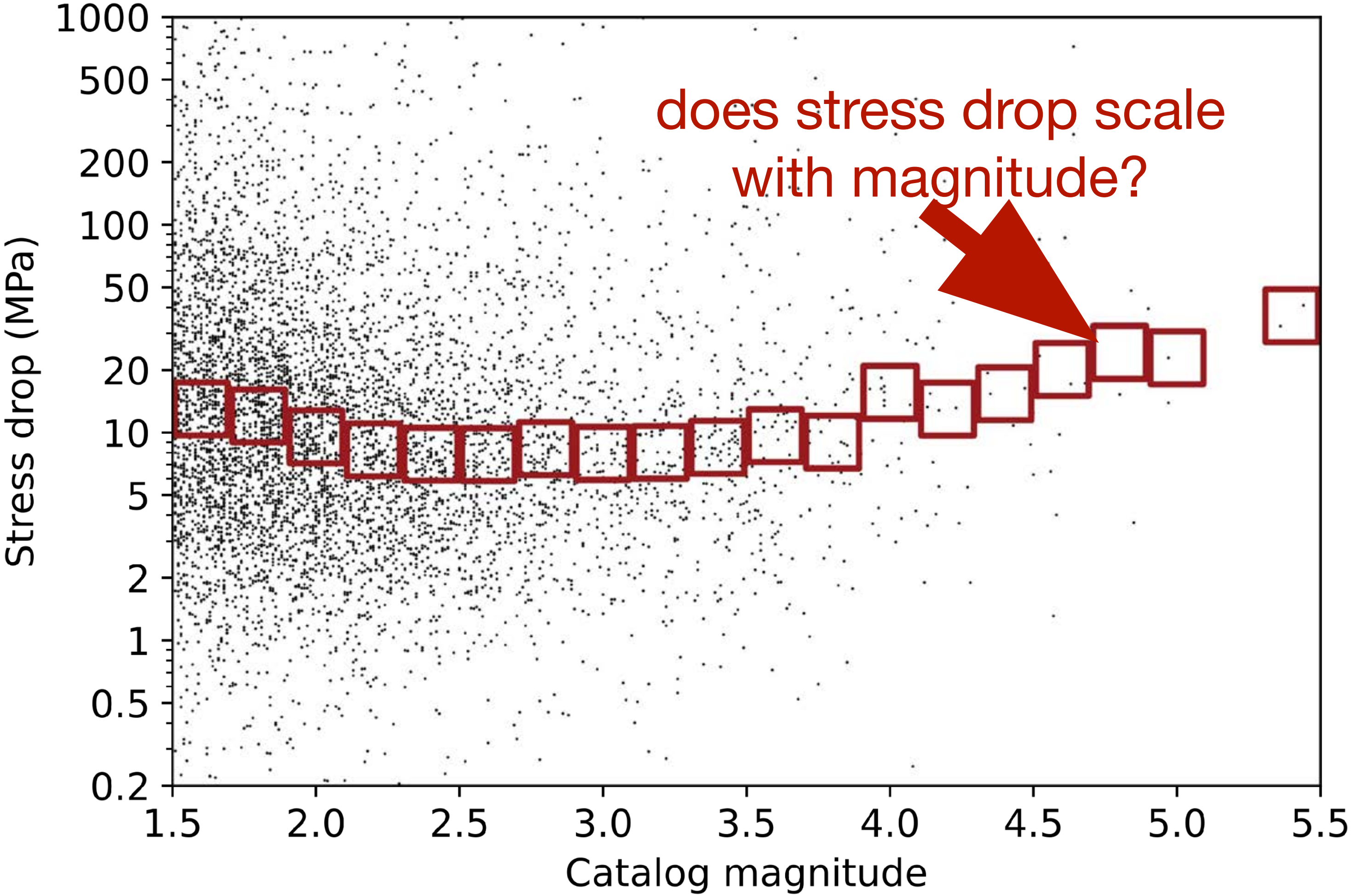


M2.5-3



M3-3.5





does stress drop scale
with magnitude?
Stress drop (MPa)
1000
500
200
100
50
20
10
5
2
1
0.5
0.2
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
Catalog magnitude