Coda Calibration Tool for Reliable Earthquake Moment Magnitude Determinations

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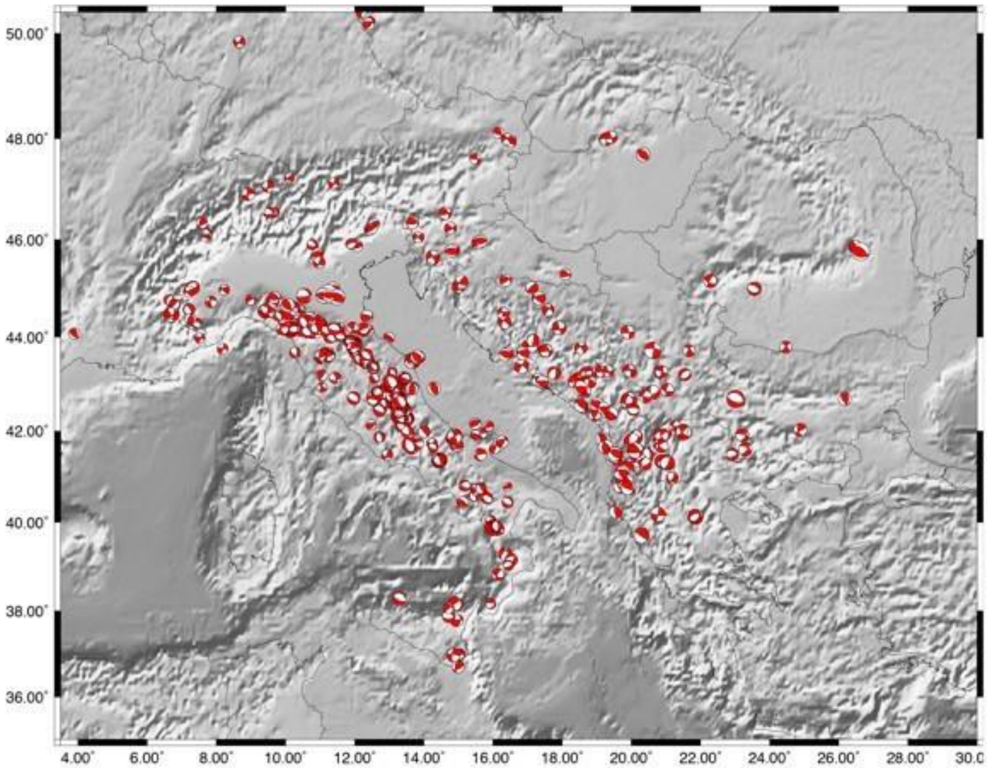
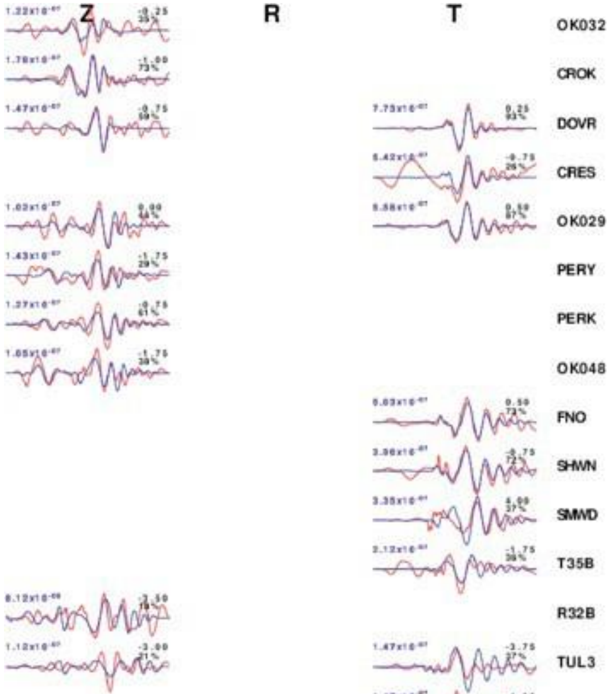
Outline

- Coda –Waves
- How to get source spectra and a moment magnitude from coda envelopes
- Using coda to get a point source estimate: CCT Methodology
- Issues you might encounter

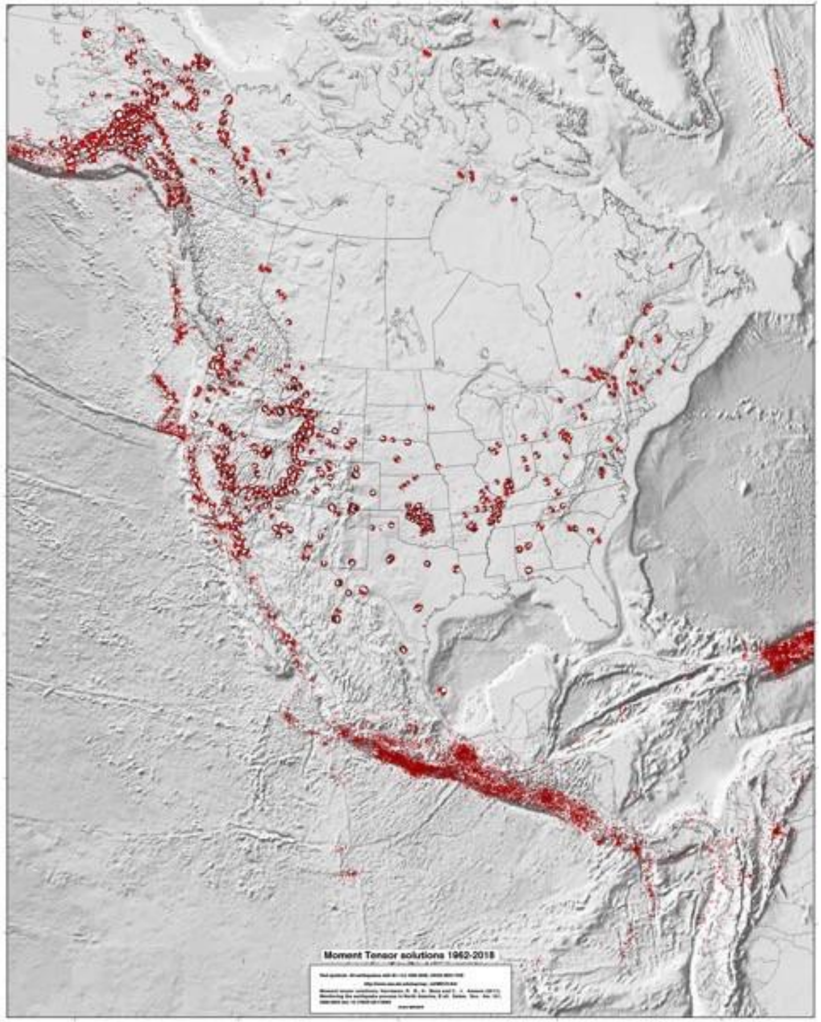
Local and regional waveform modeling can now routinely determine moment magnitudes down to ~M_W 3.5 - 4.0

For example Bob Herrmann's SLU Moment Tensor Page:
http://www.eas.slu.edu/eqc/eqcmt.html





M_W 3.47 event in Oklahoma on 9/8/18



Local and regional waveform modeling can now routinely determine moment magnitudes down to ~M_W 3.5 - 4.0

For example Bob Herrmann's SLU Moment Tensor Page:
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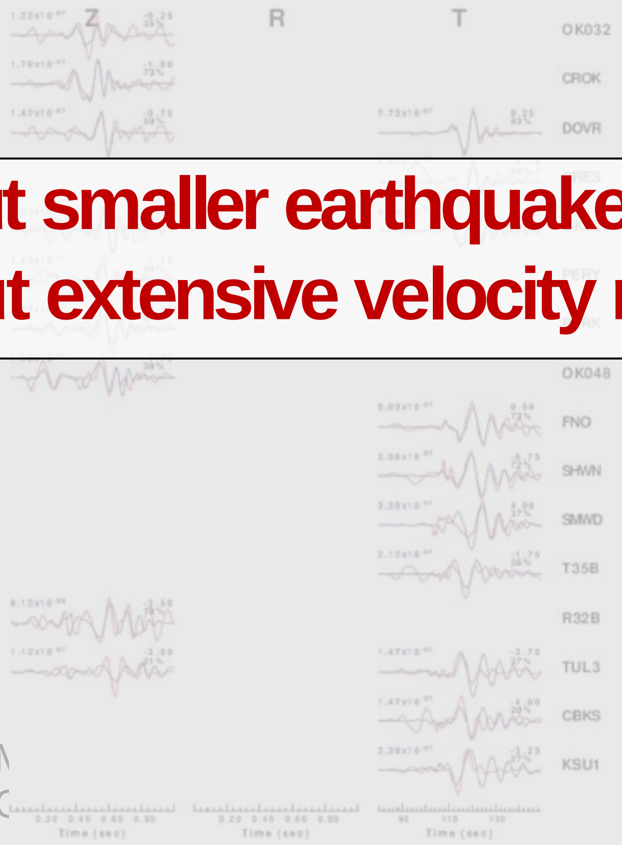
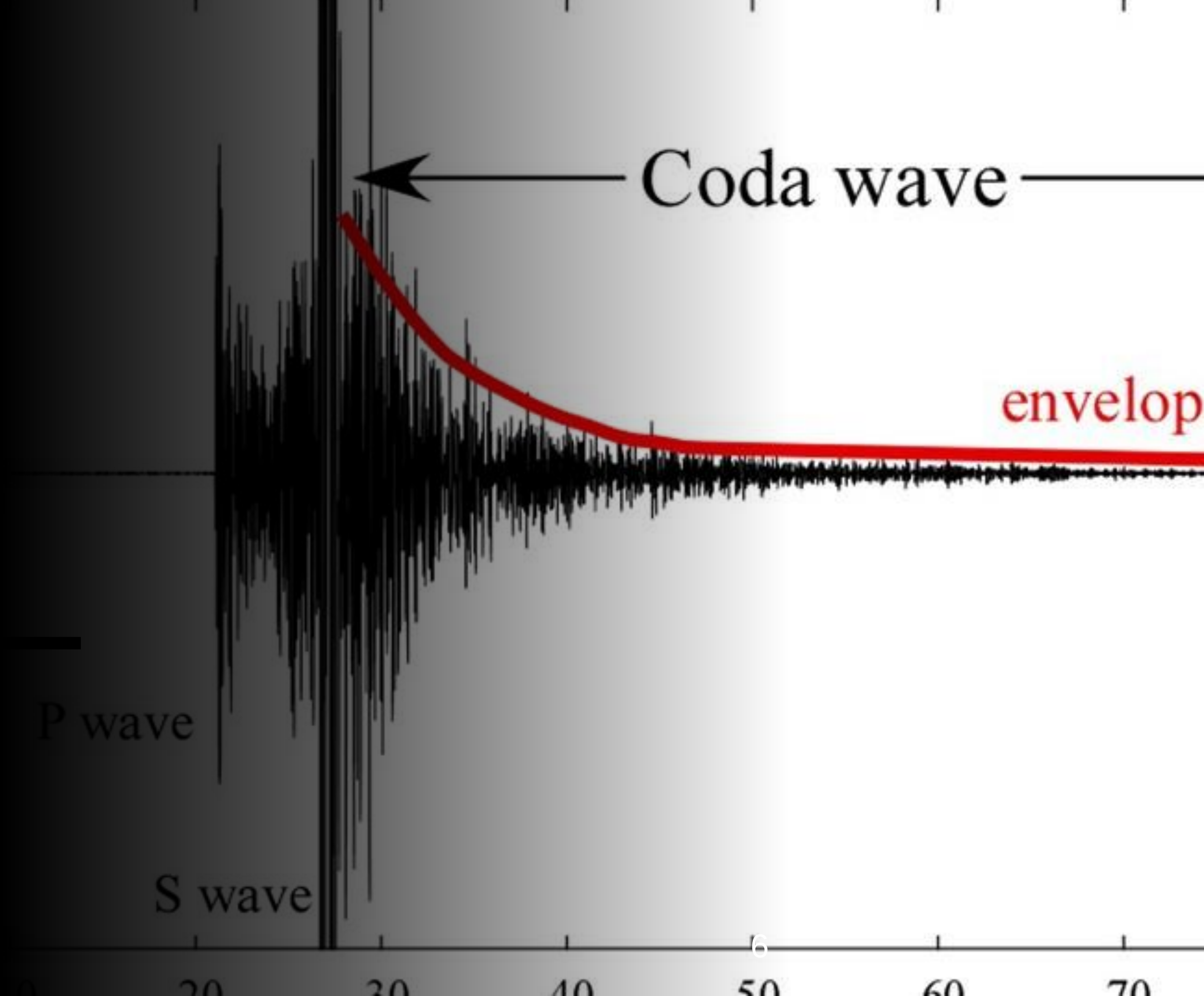
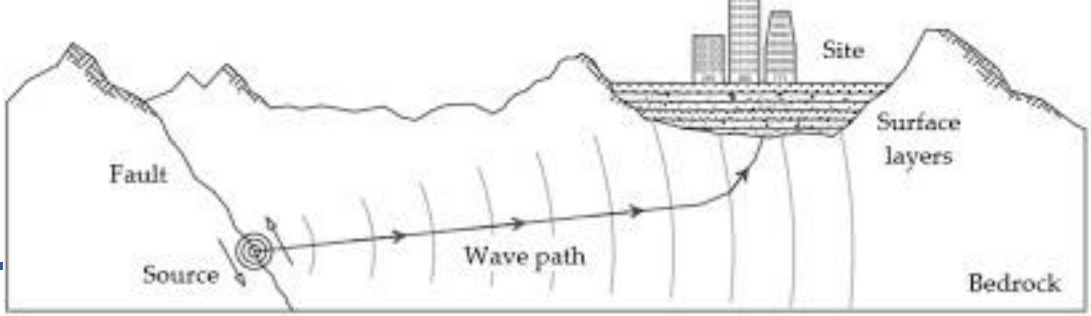


But what about smaller earthquakes or regions without extensive velocity models?

Coda waves & Coda Calibration Tool

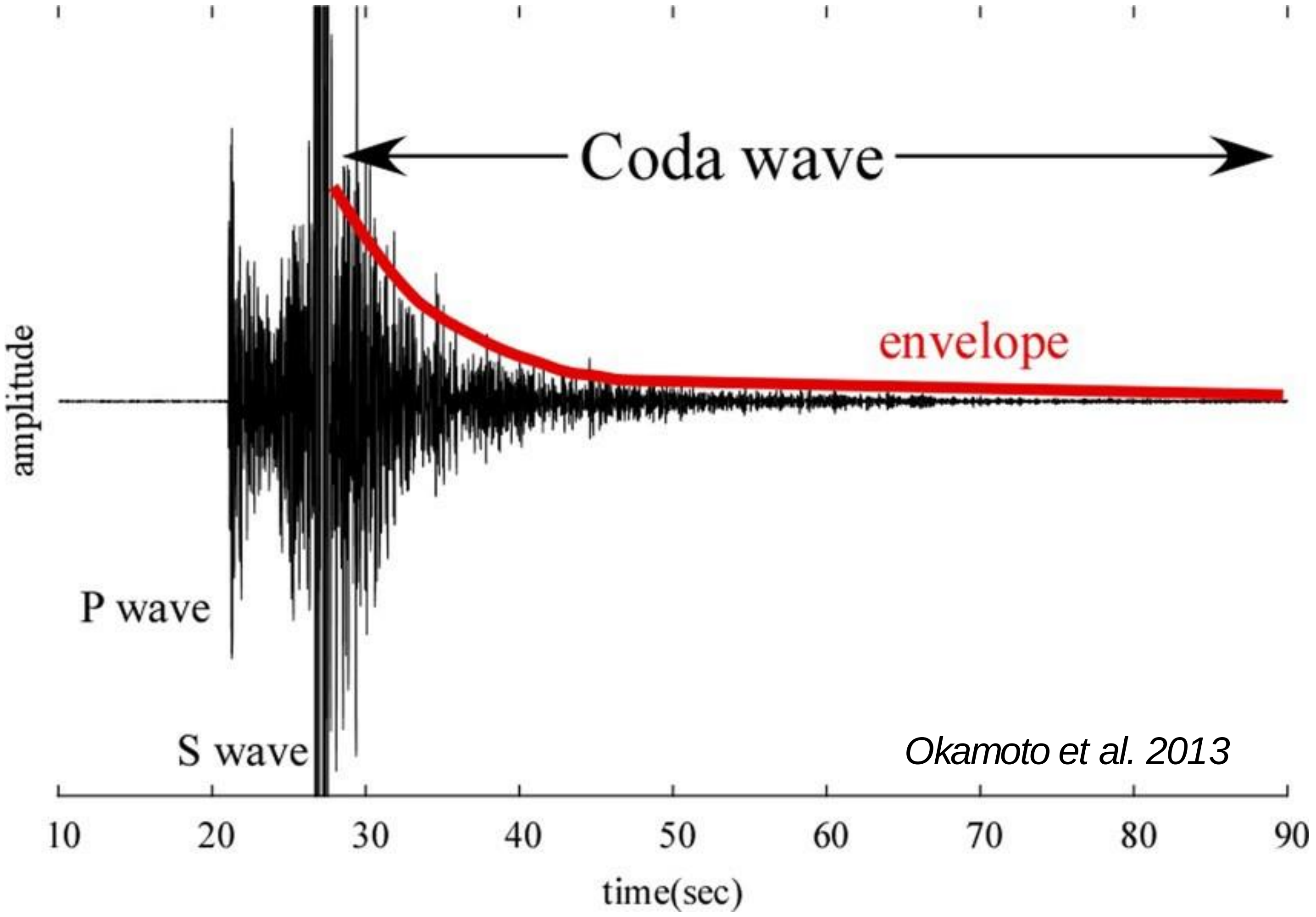


What are coda waves?



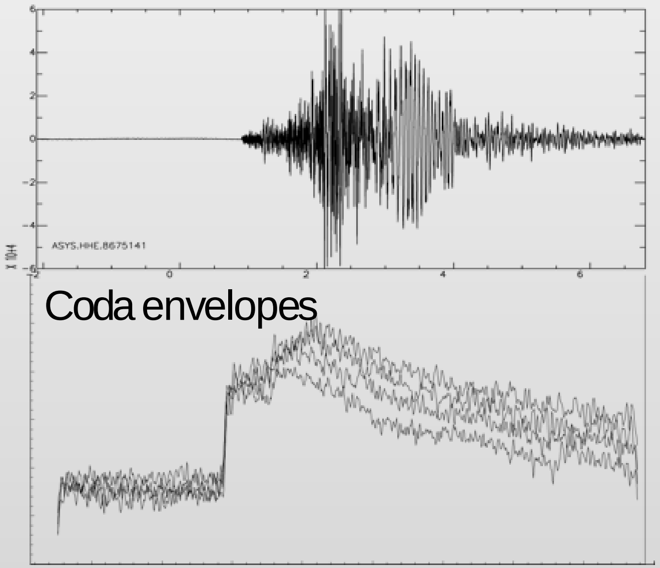
- Coda waves are the scattered waves of direct waves both P and S-waves have coda but S-coda is the most prominent.

- Coda waves have a scattering nature, therefore amplitudes derived from the envelopes average and homogenize path and source variation.

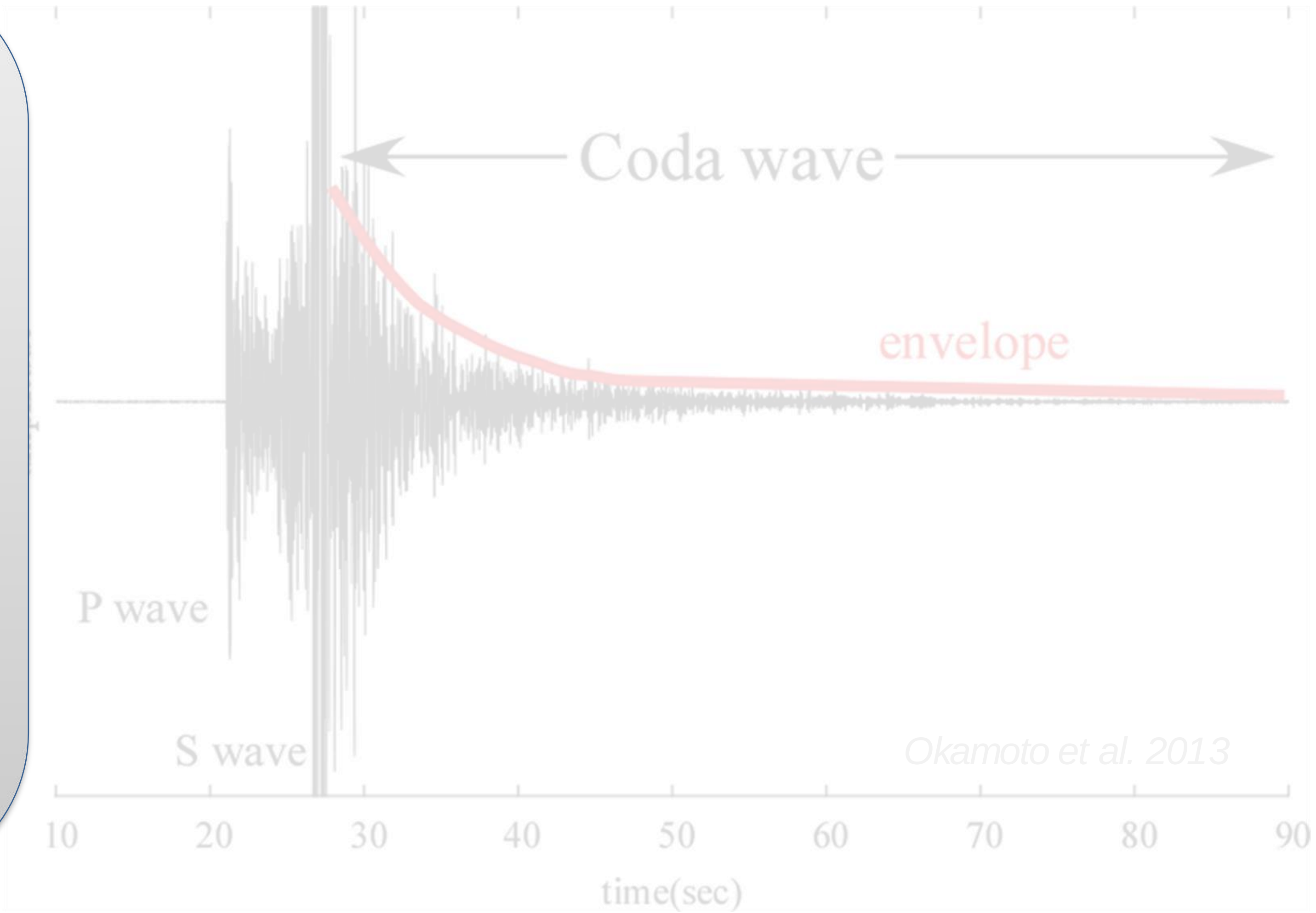


Okamoto et al. 2013

What are coda waves?

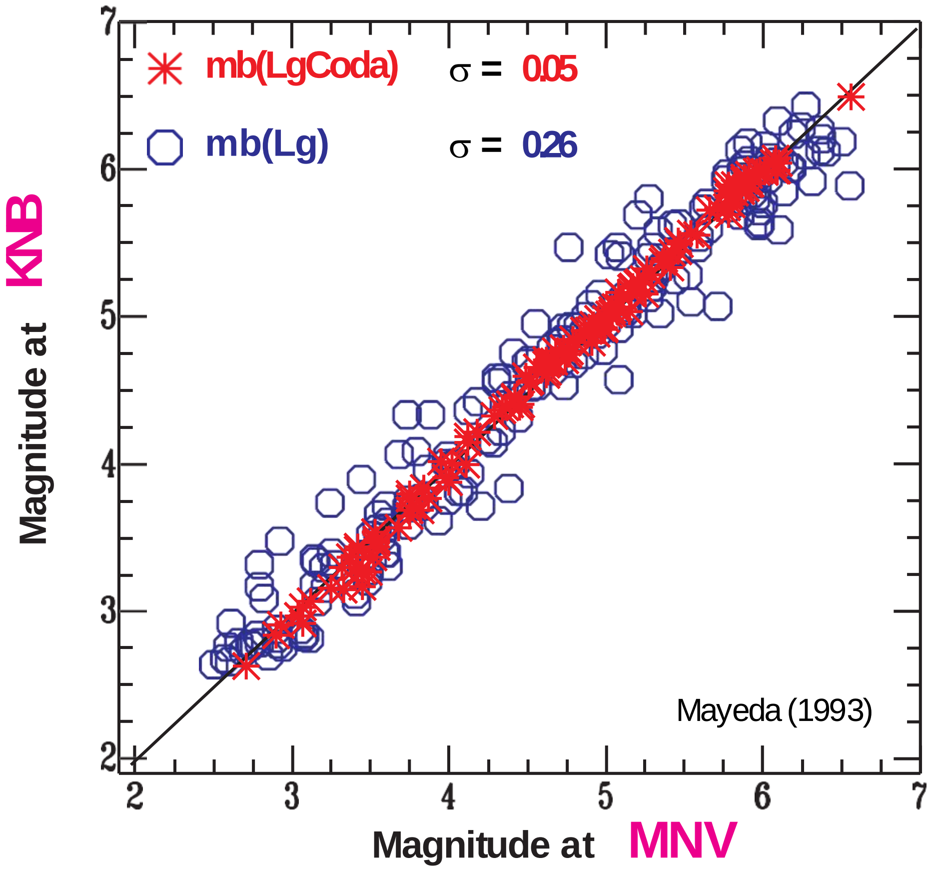


Coda waves provide a better azimuthally averaged source spectra estimate (Mayeda and Walter, 1996)

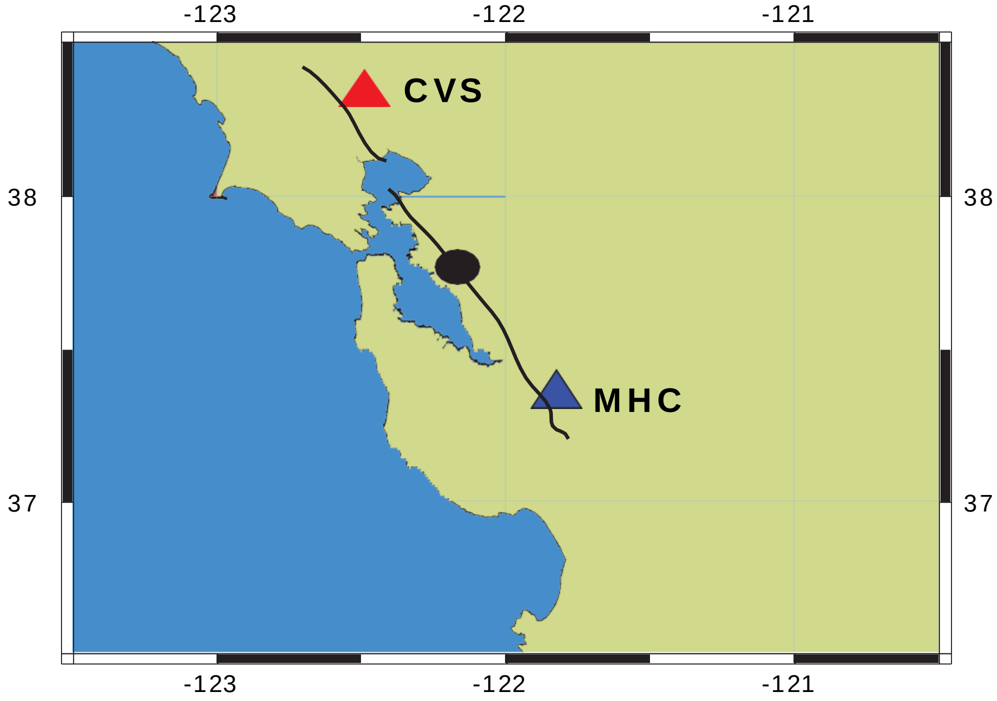


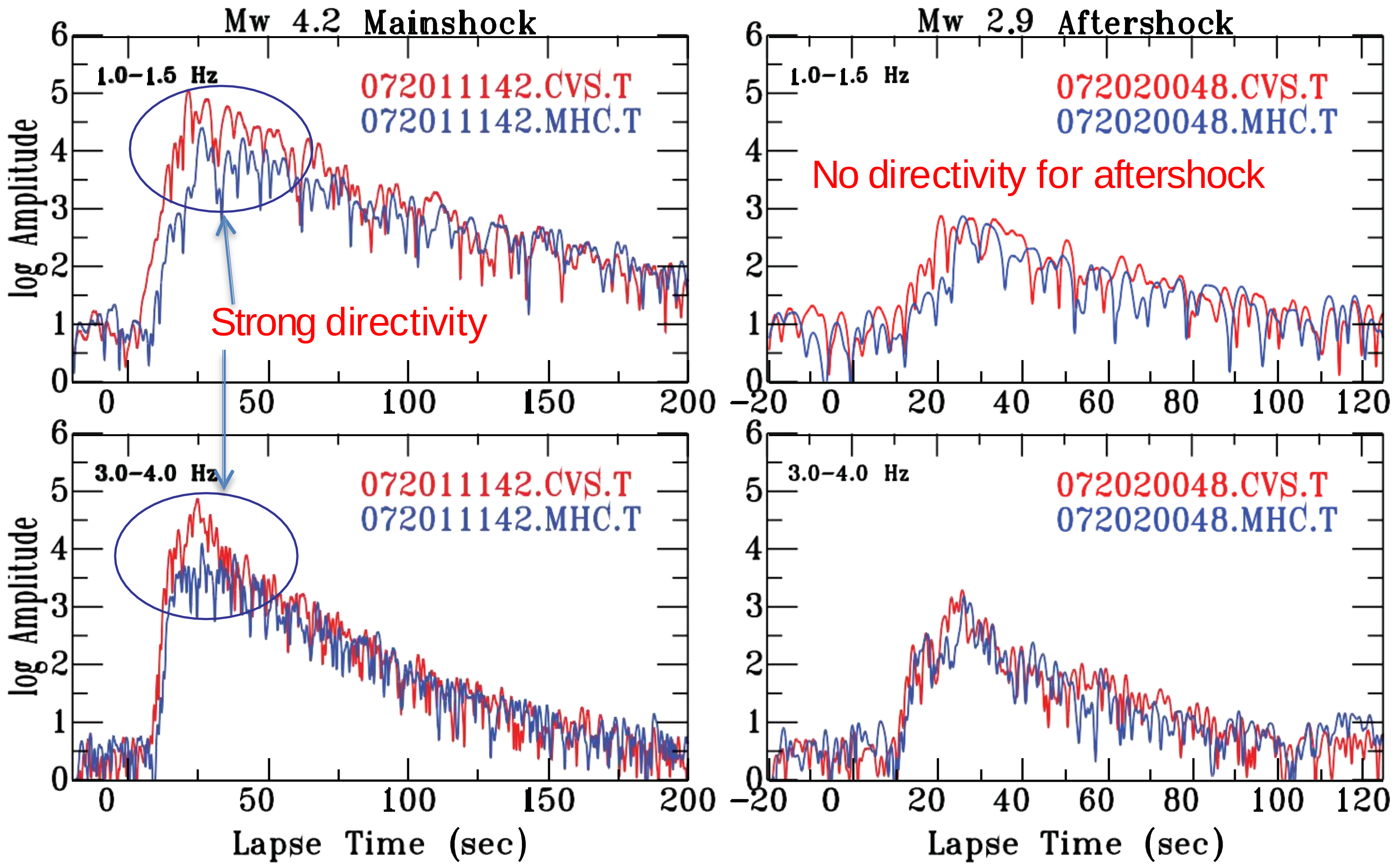
How are coda waves useful for magnitudes?

Problem:
Direct waves are sensitive to geologic structure between source and receiver as well as source radiation pattern. These issues require multiple station averaging.
Solution:
Scattered waves (Coda) average over both path and source heterogeneity. We will likely never know small length-scale features well enough for 3-D modeling, but a stochastic empirical approach has been shown to work.



Because it measures scattered energy coda is insensitive to directivity and radiation pattern as in this Mw 4.2 in Oakland

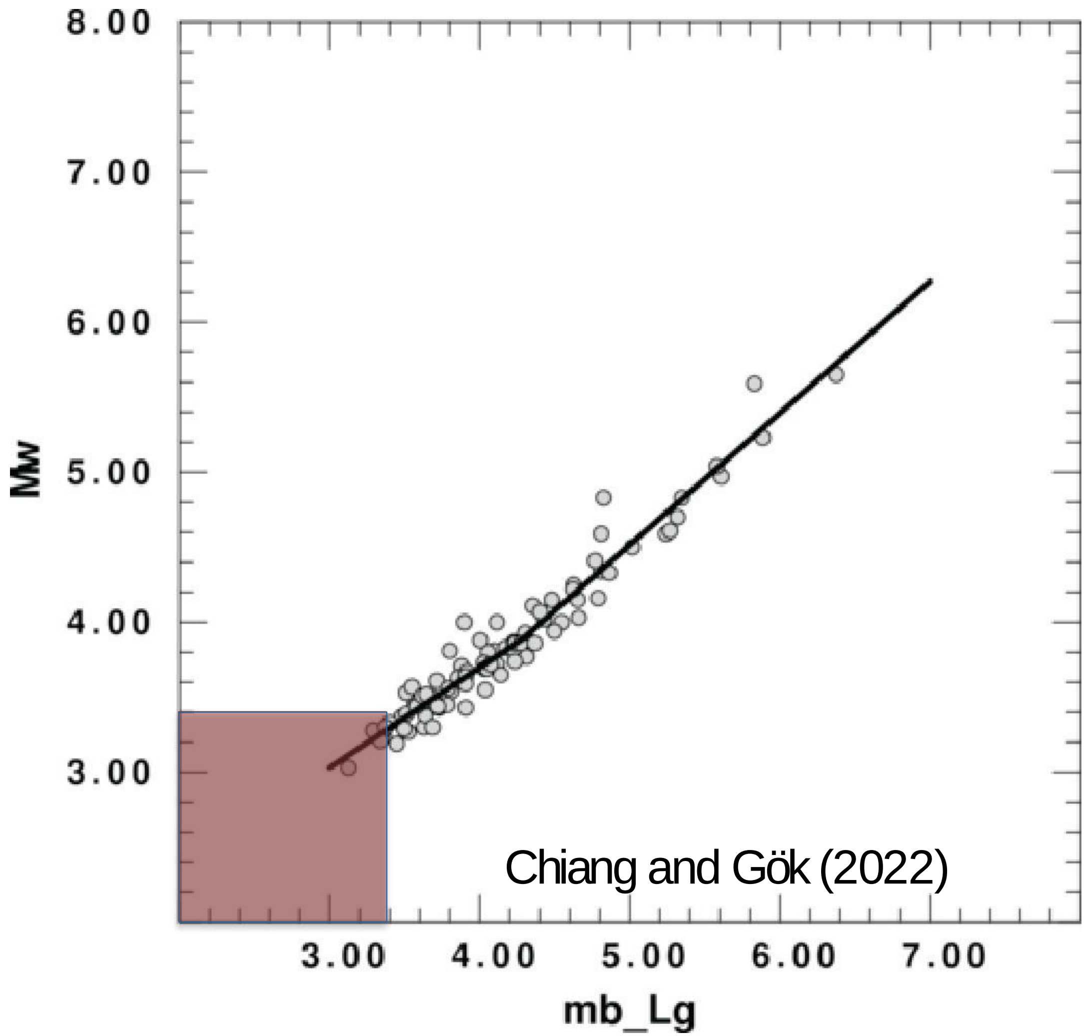




from *Mayeda & Malagnini*, 2010, GRL

Moment Magnitudes are important for source characterization and yield estimation

- Challenging to obtain moment magnitude (Mw) for smaller events
- The relationship between narrow band magnitudes and Mw are not linear:



Coda Calibration Tool Methodology

Open-Source Coda Calibration Tool available through GitHub

You can access the Coda Calibration Tool (CCT) here:

Required Java: https://adoptium.net/
CCT Tutorial: https://software.llnl.gov/coda-calibration-tool/
CCT Code: https://github.com/LLNL/coda-calibration-tool

This tool is under active development and we welcome feedback ^.^
***Every 3rd Thursday Meeting of CCT users worldwide (8:00 am Pacific time)**

Coda Calibration Methodology: DATA

- **Data Required:**
  - **Instrument corrected regional velocity waveforms. (mseed or sac)**
  - **Horizontal components**
  - **200s before and 1500/2000s after event (dependent on EQ size)**
  - **Reference Events –** a few events where Mw has been calculated with waveform modeling.
  - Min Events for Region: at least 20-30 earthquakes with 5-10 reference events with Mw. -> emphasis on even distribution of space and magnitude
    - *It is recommended to make two separate calibration by depth Shallow (0-5 km) and Deeper (> 5km)
    - Frequency bands should extend no higher than Nyquist Frequency (1/2 smprt)

Coda Calibration Methodology: DATA

- Data Required:
  - Instrument corrected regional velocity waveforms.
  - Horizontal components
  - 200s before and 1500/2000s after event (dependent on EQ size)

Why Velocity Horizontal Waveforms?

- Swaves have larger signal-to-noise ratio
- averaging the two provides a smother envelope than a single component alone
- Can be done on single component – but this is less desirable
- Alternatively, can incoherently stack envelopes from short-period vertical array stations, which can significantly reduce the pre-event noise. Square root of n reduction.

Coda Calibration Methodology:

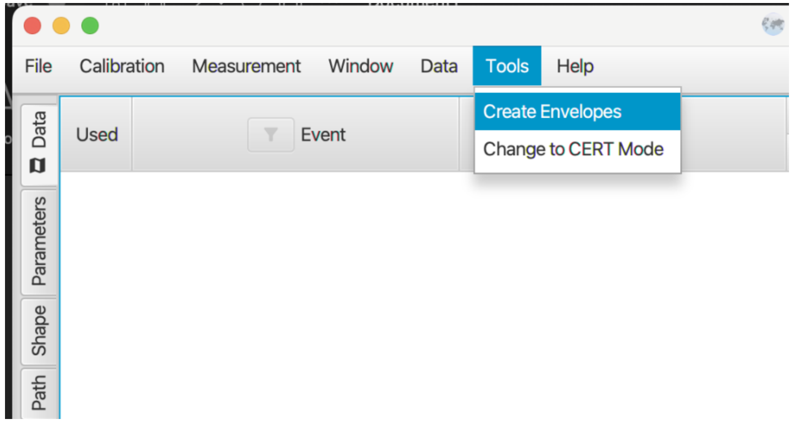
Procedure to Calibrate Seismic Stations

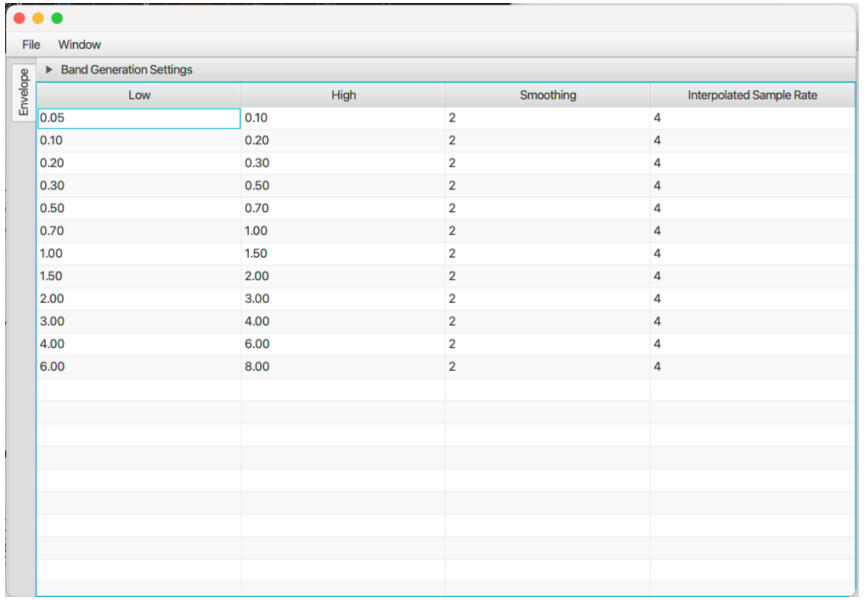
1. Form Narrowband Envelopes
2. Measure the move-out velocity of the peak S-wave envelope
3. Fit the observed coda envelopes with empirical synthetics
4. Apply empirical distance corrections
5. Tie the distance-corrected coda amplitudes to independent seismic moment determinations using long-period waveform modeling.

Coda Calibration Tool (CCT)

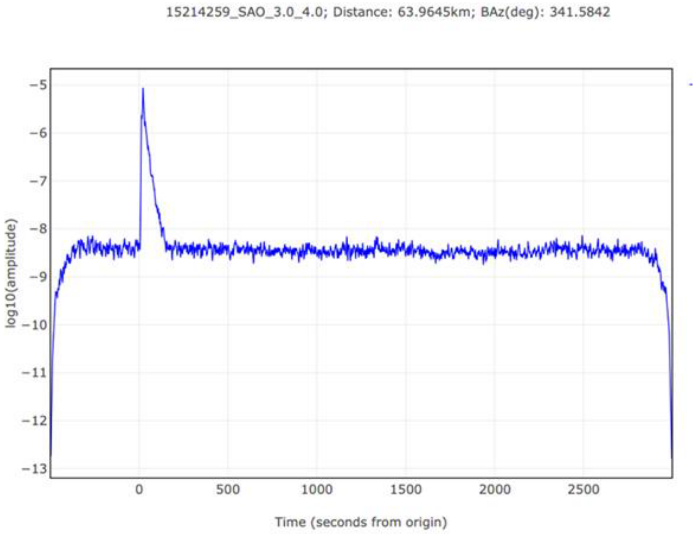
Steps to measure source spectra and Mw

- Creating Envelopes
  - — Two horizontal component envelopes are formed by taking the Hilbert transform at narrow filtered frequency bands and stacked
  - — This is done in the tool all the user needs to provide is the desired frequency bands and sac waveform files.





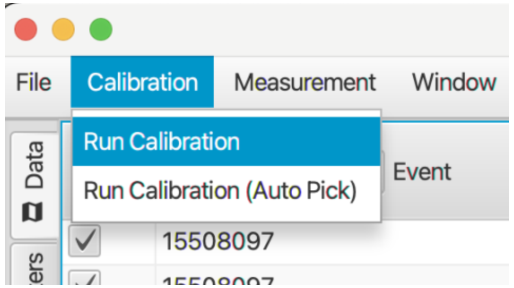
Low	High	Smoothing	Interpolated Sample Rate
0.05	0.10	2	4
0.10	0.20	2	4
0.20	0.30	2	4
0.30	0.50	2	4
0.50	0.70	2	4
0.70	1.00	2	4
1.00	1.50	2	4
1.50	2.00	2	4
2.00	3.00	2	4
3.00	4.00	2	4
4.00	6.00	2	4
6.00	8.00	2	4

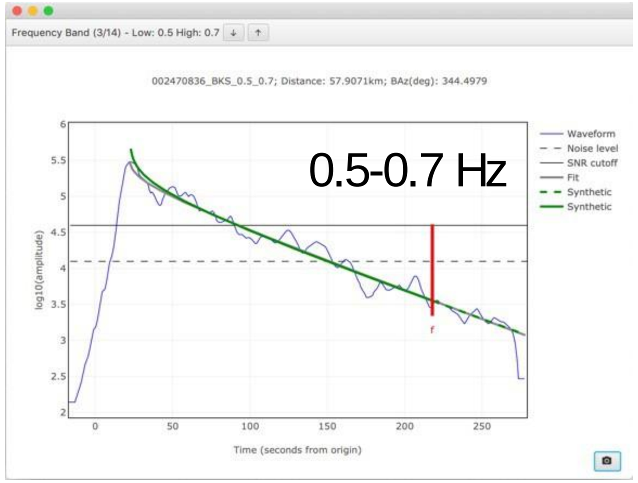


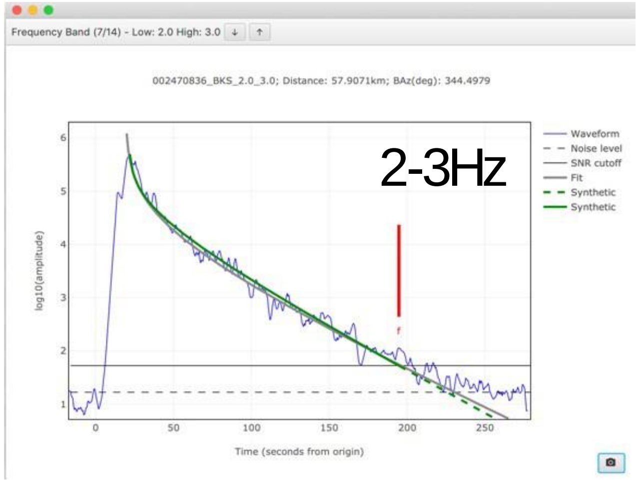
Coda Calibration Tool (CCT)

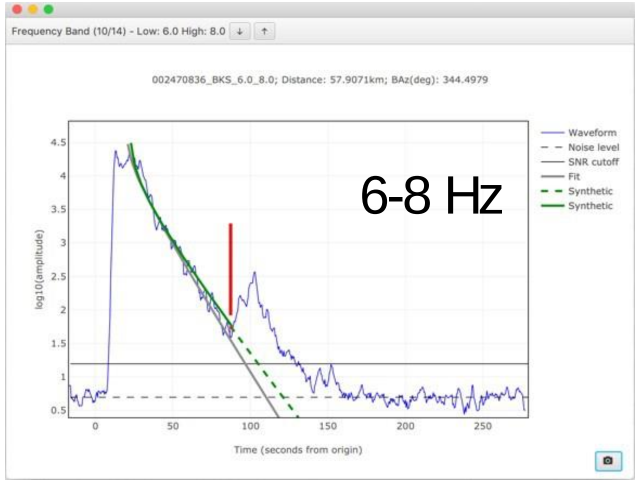
Steps to measure source spectra and Mw

- Measure narrowband coda envelopes
  - The envelope peak velocity function represented by a simple hyperbola, is obtained from the measured peak amplitude arrivals and envelope start and shape functions.
  - This is fitted and the end of coda is picked automatically by the tool but can be edited by the user. The automatic picker can be adjusted to improve autopicking depending on desired users needs.







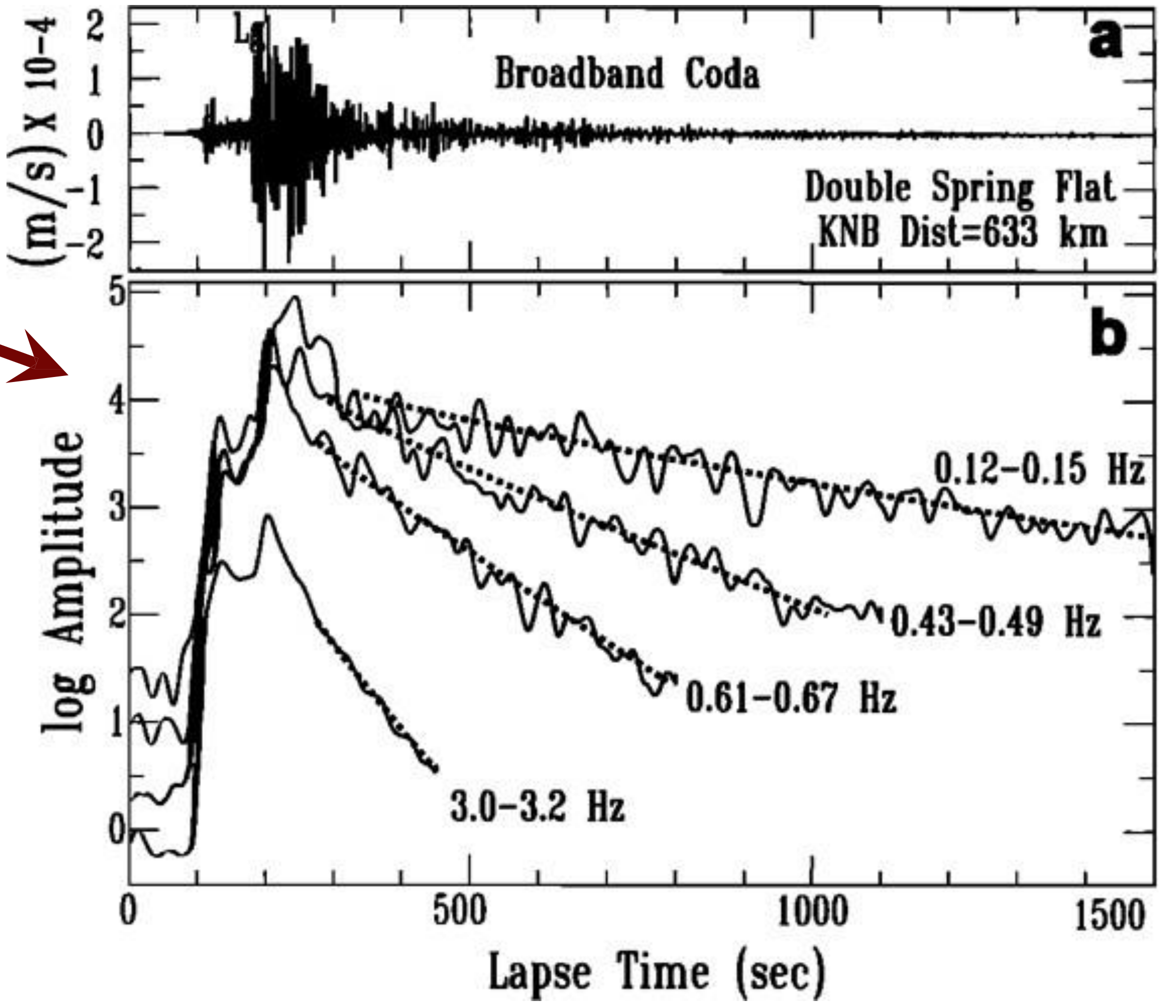


Coda Calibration Tool (CCT)

Steps to measure source spectra and Mw

(Mayeda and Walter, 1995)

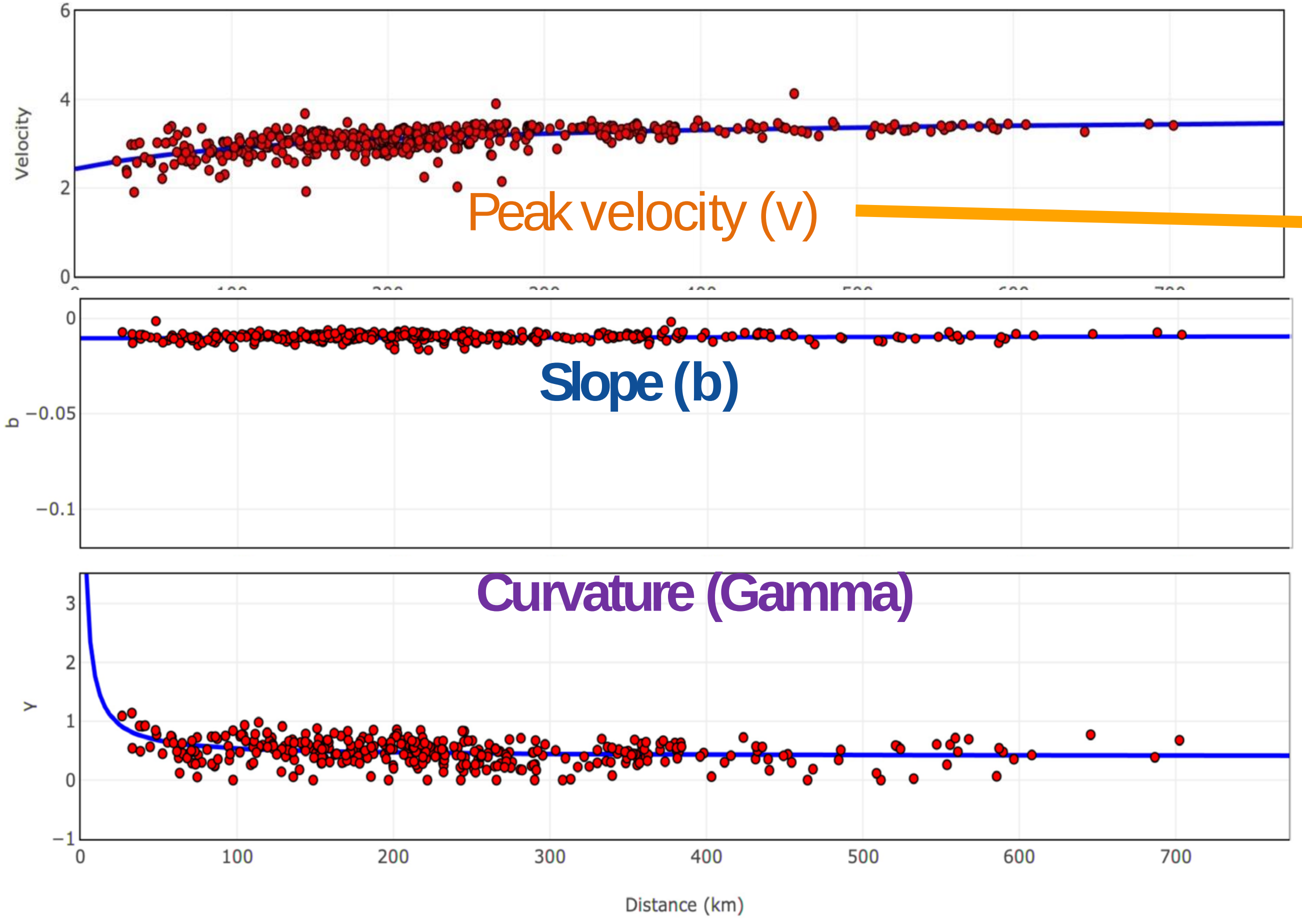
The duration of visible coda varies with frequency.

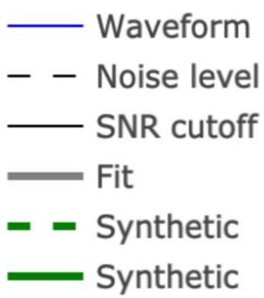


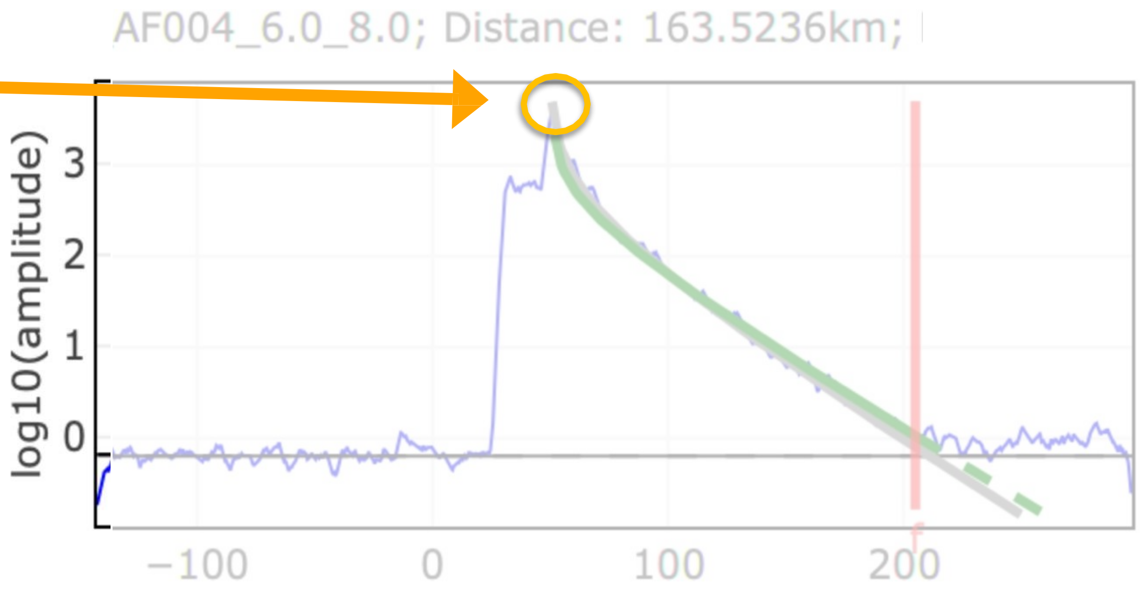
- ► Coda is best viewed by taking the envelope of the signal in a narrow frequency band and looking at the log amplitude versus time

Coda Calibration Tool (CCT)

Steps to measure source spectra and Mw



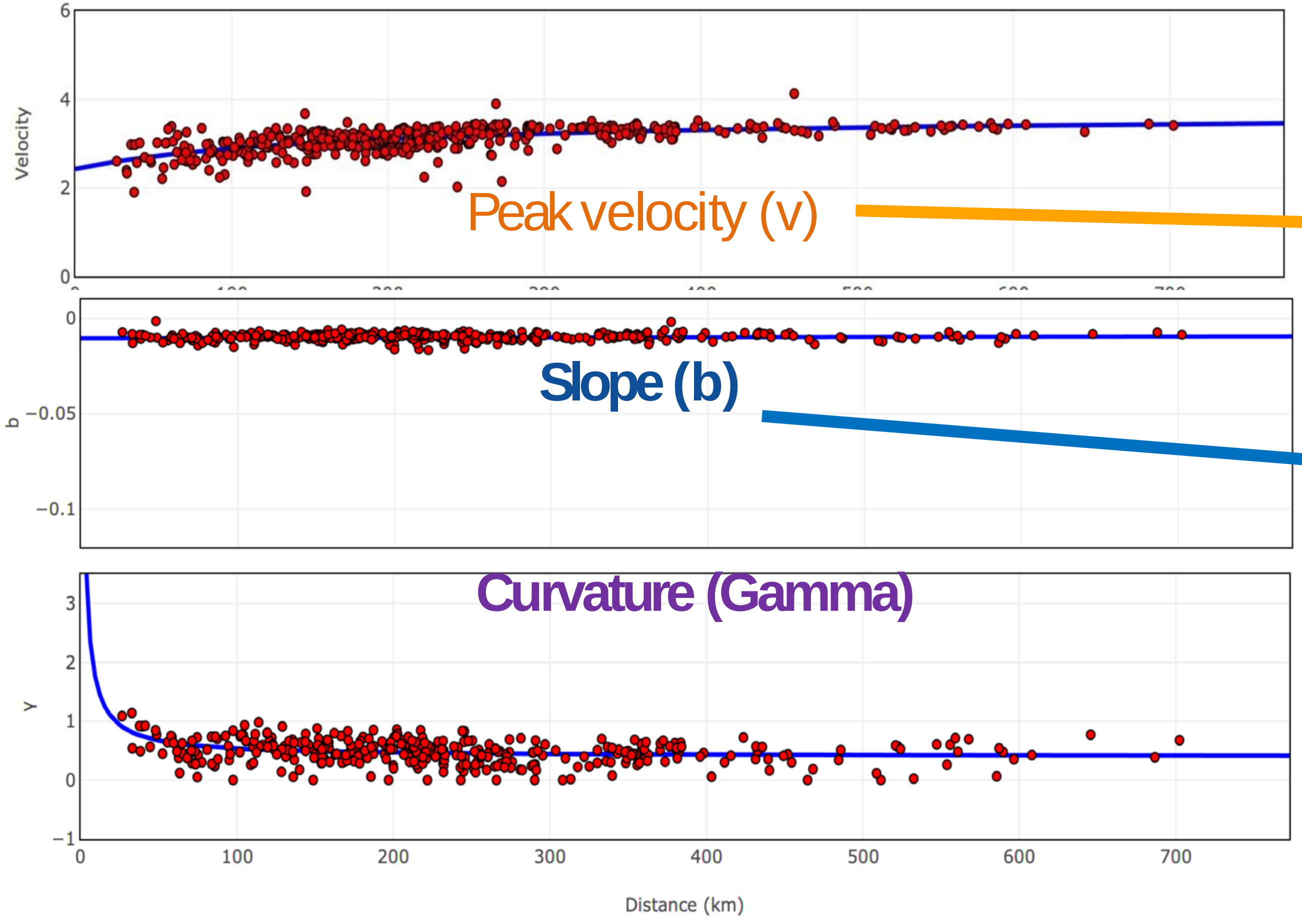


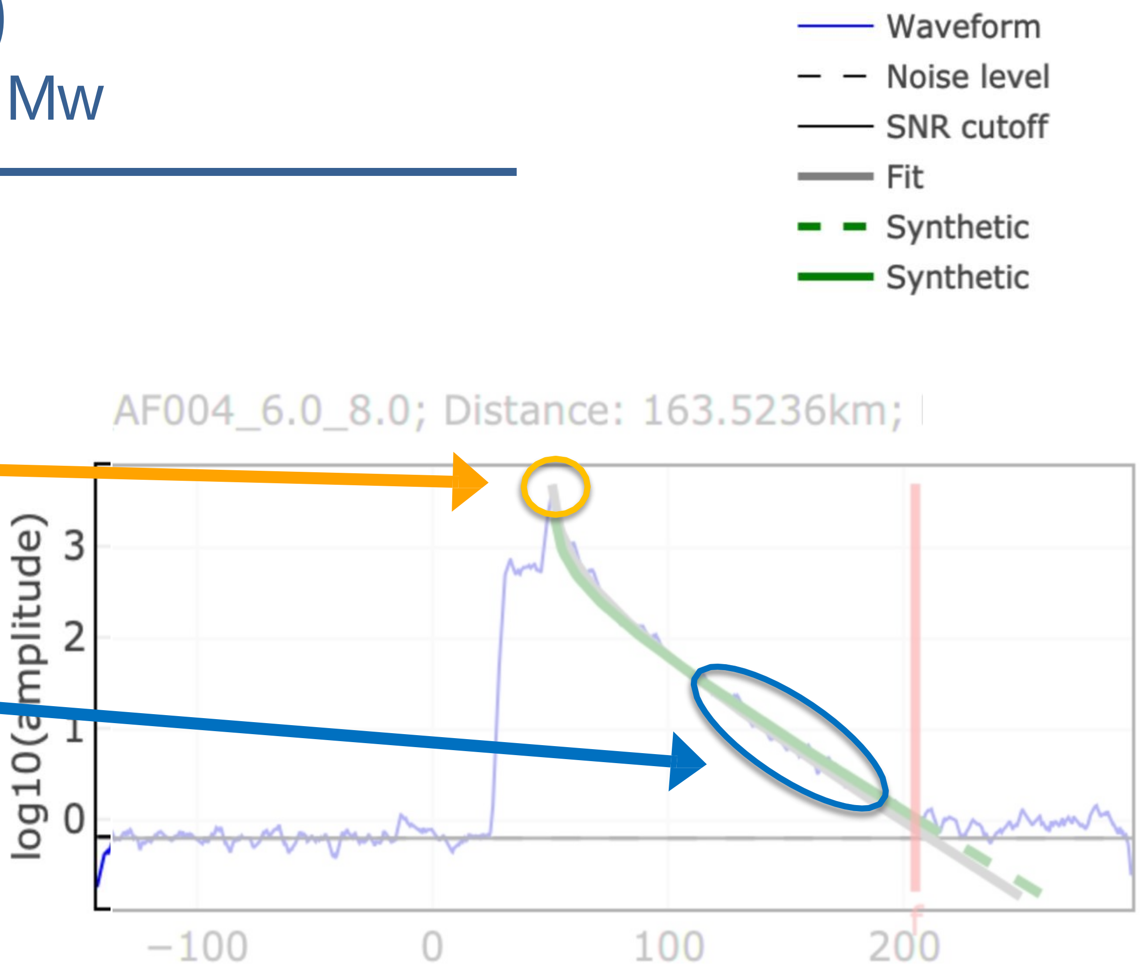


- Peak velocity, slope, and curvature are the empirical shape parameters and fits to the overserved data as a function of station distance.

Coda Calibration Tool (CCT)

Steps to measure source spectra and Mw





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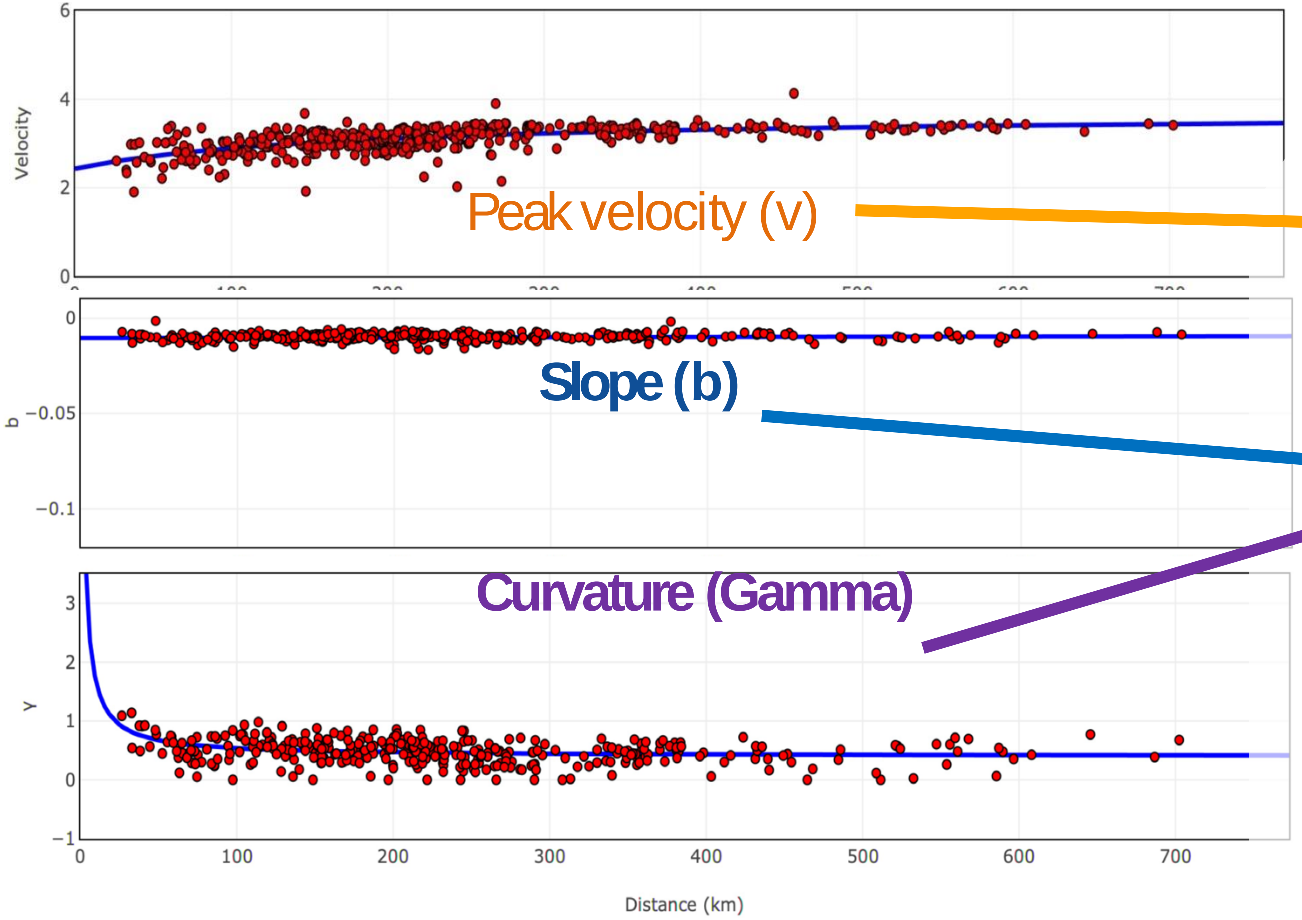
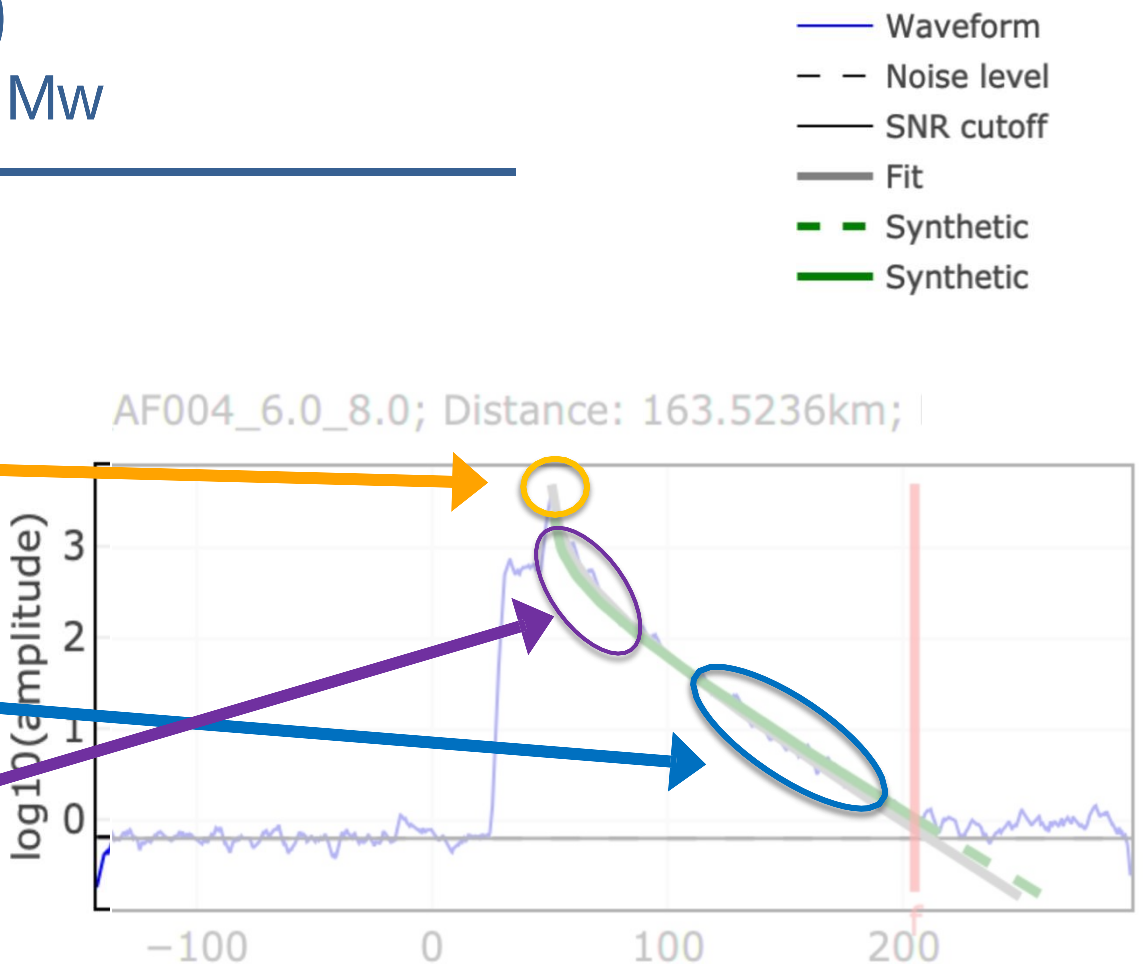
Steps to measure source spectra and Mw





- Peak velocity, slope, and curvature are the empirical shape parameters and fits to the overserved data as a function of station distance.

Coda Calibration Methodology:

Procedure to Calibrate Seismic Stations

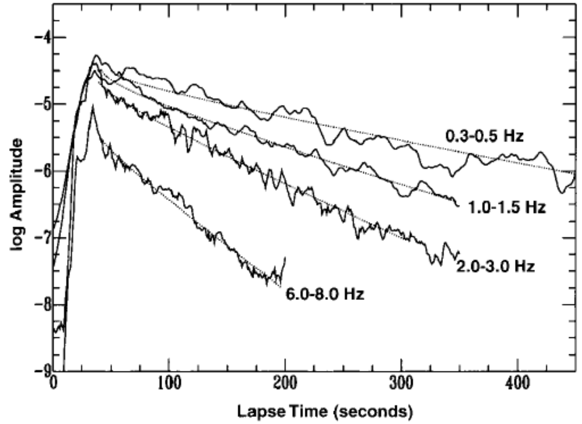
*Empirical Procedure Accounts for:

- Propagation
- Site
- S-to-Coda transfer function effects

- Results in coda-derived moment-rate spectra used to provide stable unbiased and unsaturated magnitude

Coda Envelope
Definition

Analytic expression used to fit the observed narrowband envelopes at the center frequency **f** as a function of distance **r** for times **t** greater than the direct Sarrival



Coda envelope of an event at a station

Site amplification term

Path attenuation

$$A_c(f,t,r) = W_0(f)S(f)T(f)P(r,f)H\left(t - \frac{r}{v(r)}\right)\left(t - \frac{r}{v(r)}\right)^{-\gamma(r)} \exp\left[b(r)\left(t - \frac{r}{v(r)}\right)\right]$$

Coda envelope shape function

Source amplitude

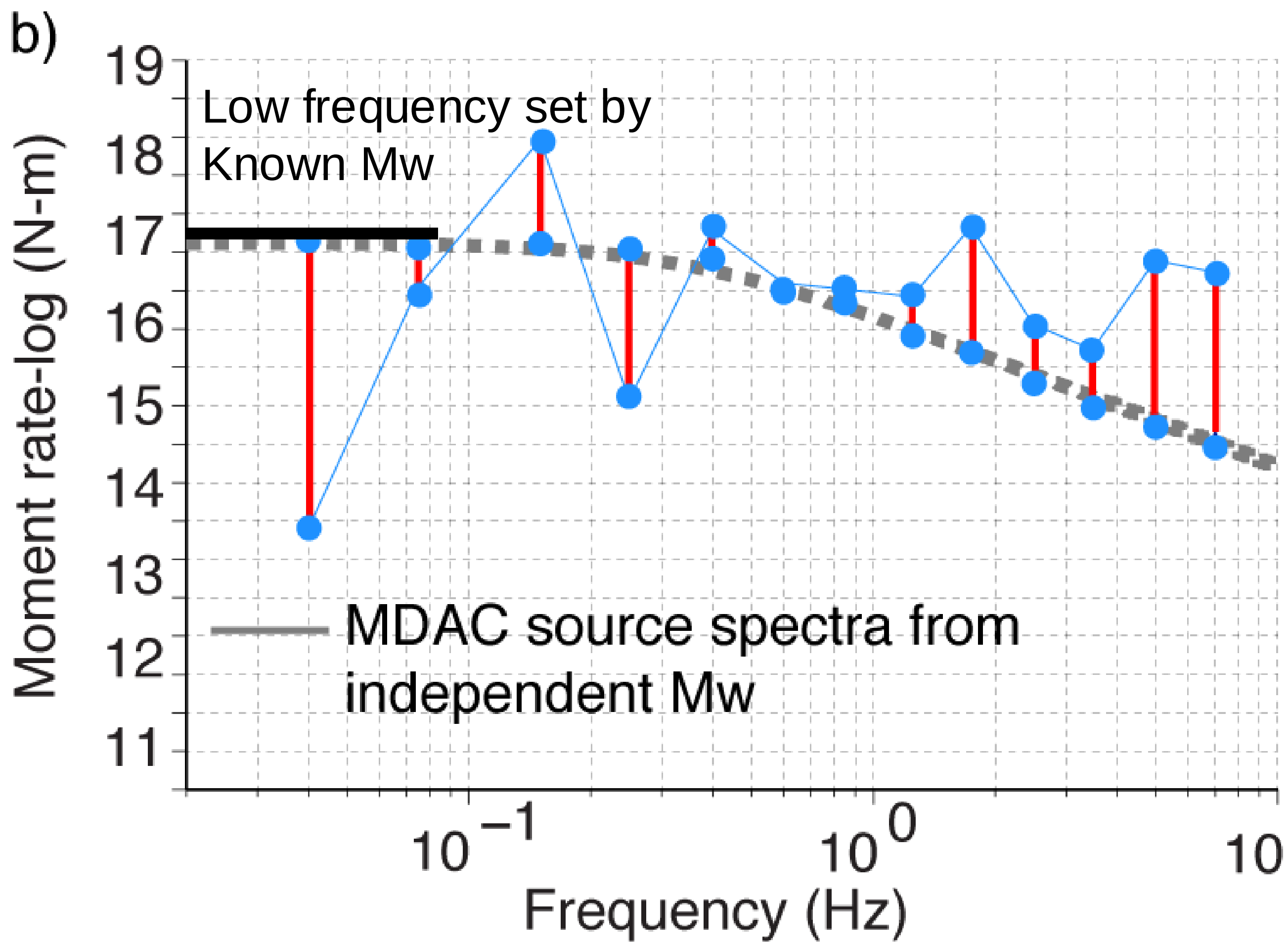
S-to-Coda transfer function

Heaviside step function

v(r) is the peak velocity
γ(r) and b(r) are the distance-dependent coda shape factors that control the coda envelope shape

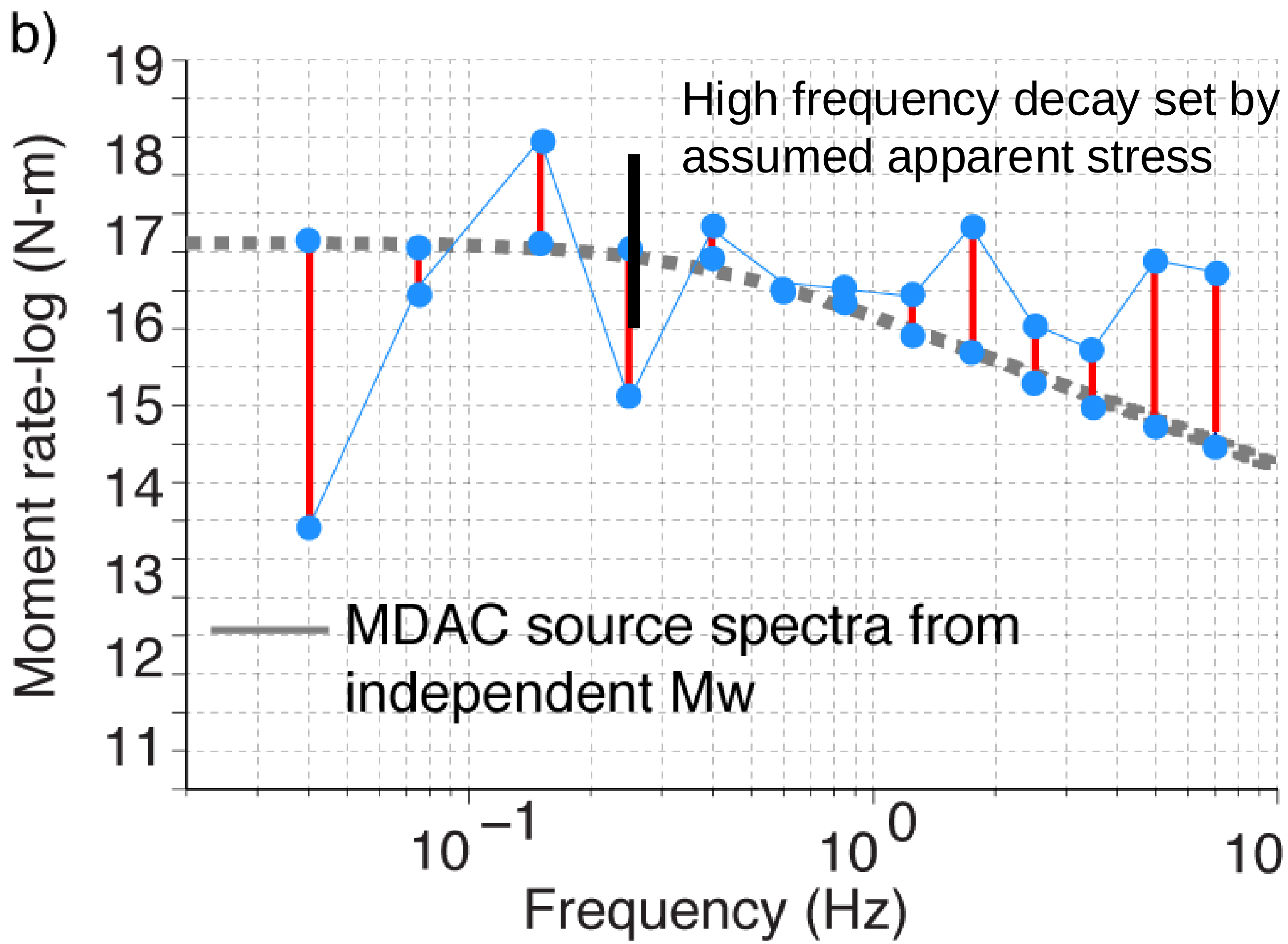
Path and Site Corrections

- CCT corrects the observed source spectra to that of a general Brune model. These corrections are used to estimate path and site specific corrections.
- The Brune model's lower frequency asymptote used to correct the spectra is based on previously determined Mw estimated usually by wave modeling (Moment Tensor estimate)

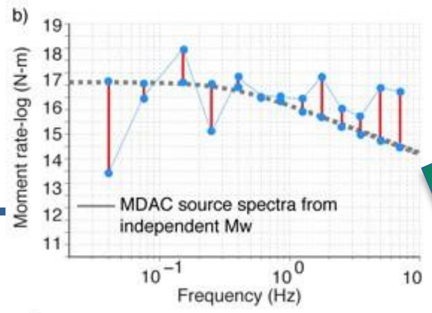


Path and Site Corrections

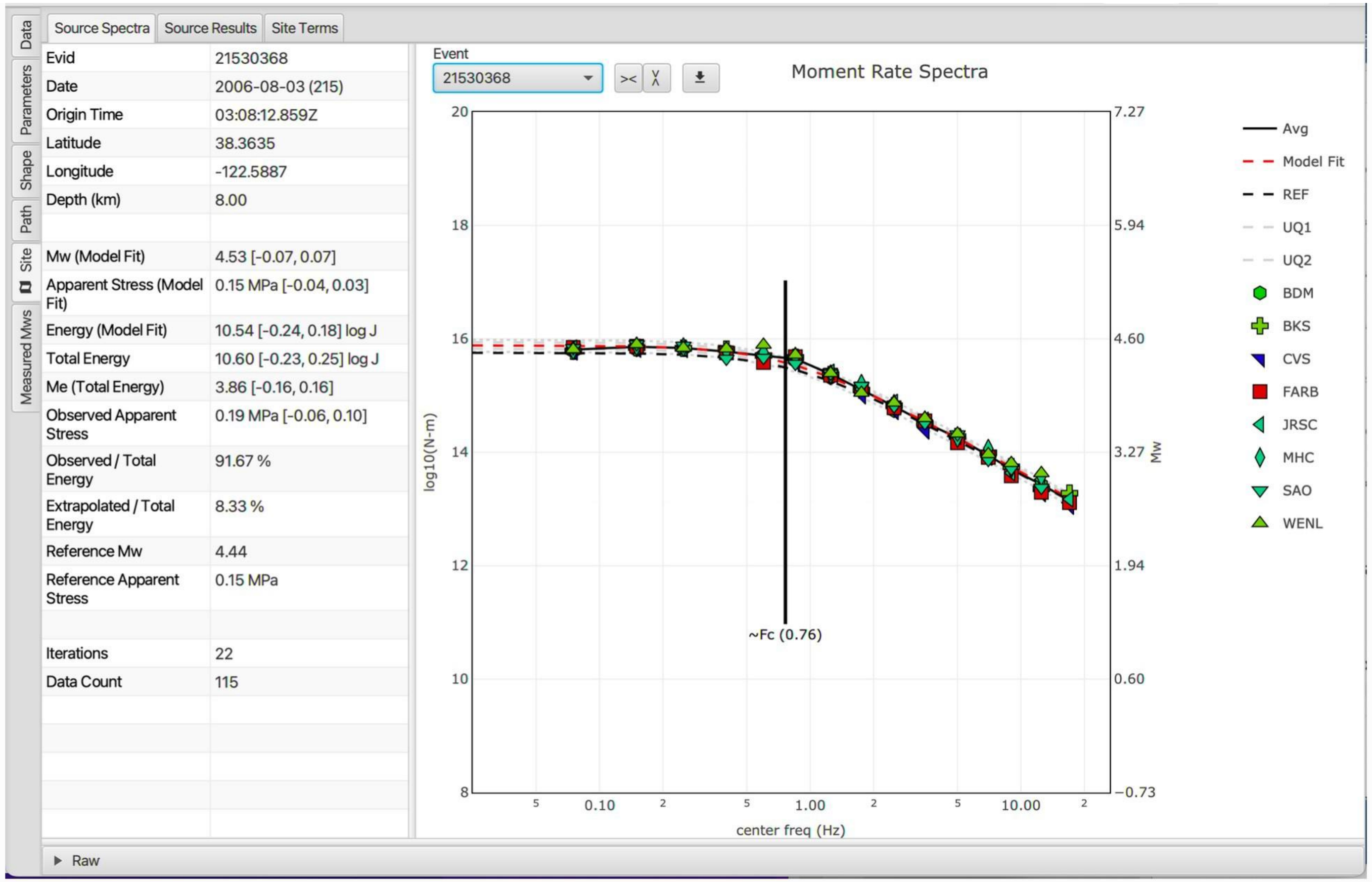
- The high frequency decay of the Brune model used to correct the spectra assumes an apparent stress of 0.3 Mpa (Stress Drop of 1.29).
- A user can set the assumed stress drop for the event themselves as well if they have an independent estimate of a reference events apparent stress or stress drop.



Path and Site Corrections

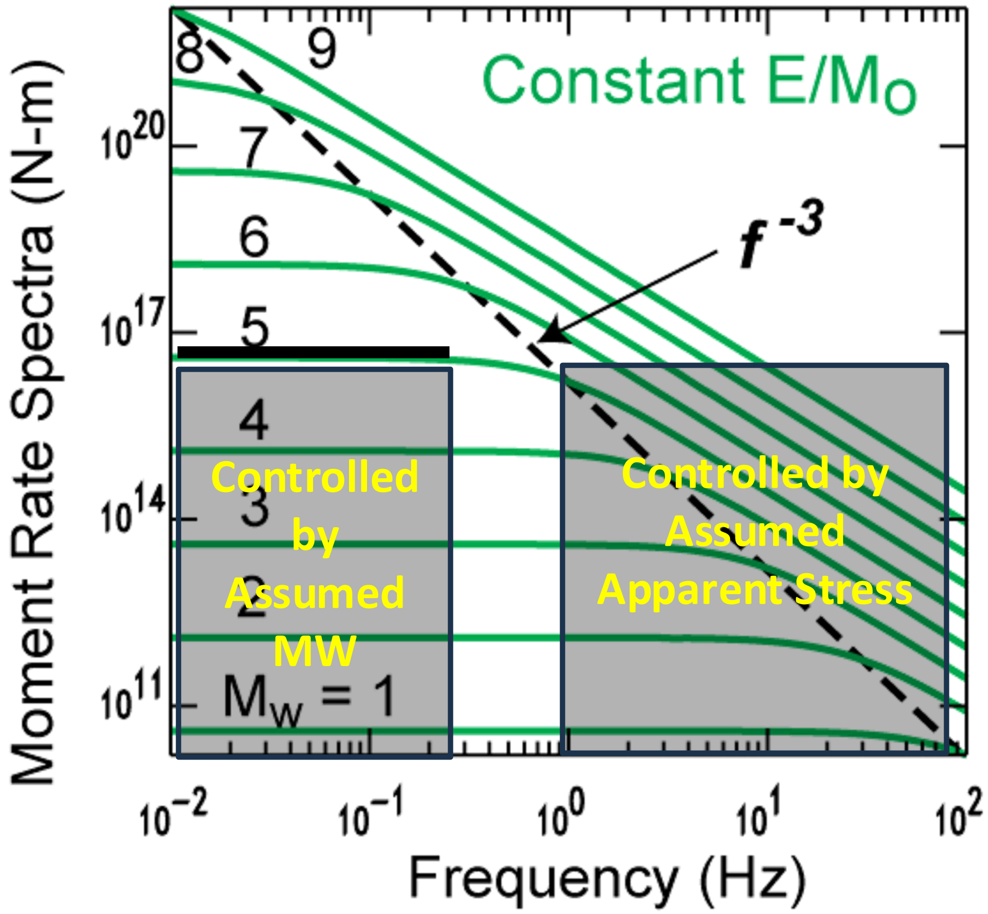


- CCT enables the determination of frequency dependent site effects and coda excitation factor to provide moment rate spectra
- Measure the shift needed to correct site specific effects and align to the reference source spectra
- Tie to previously determined Mw



Assumed Apparent stress effects

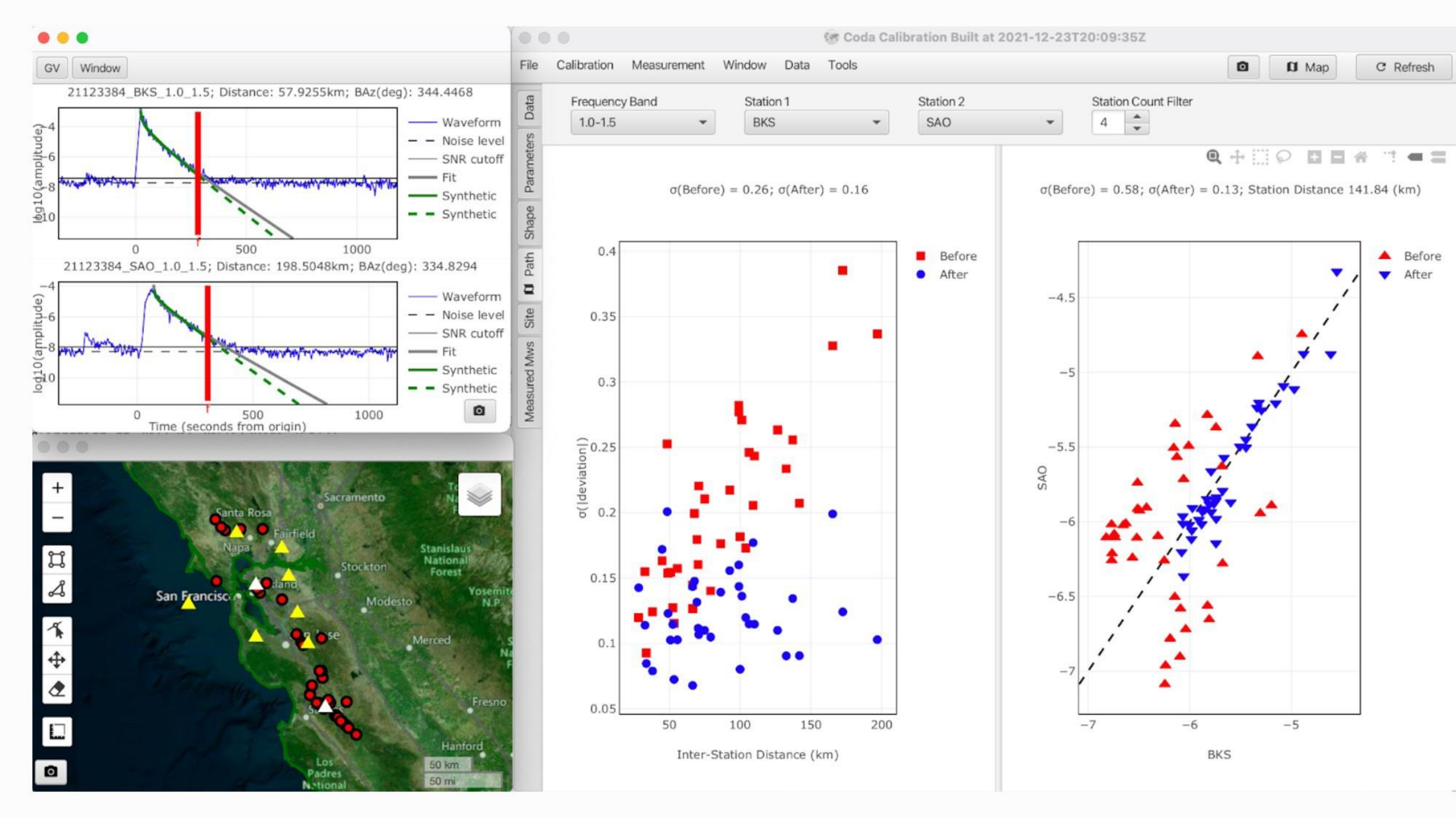
- Moment Tensor estimates of Mw's are often highly reliable making the low frequency correction robust.
- The high frequency correction could affect any lower magnitudes estimates of Mw and estimates of corner frequency
- Assumed apparent stresses/stress drop used should be well documented and could be a source of bias depending on method of estimation.



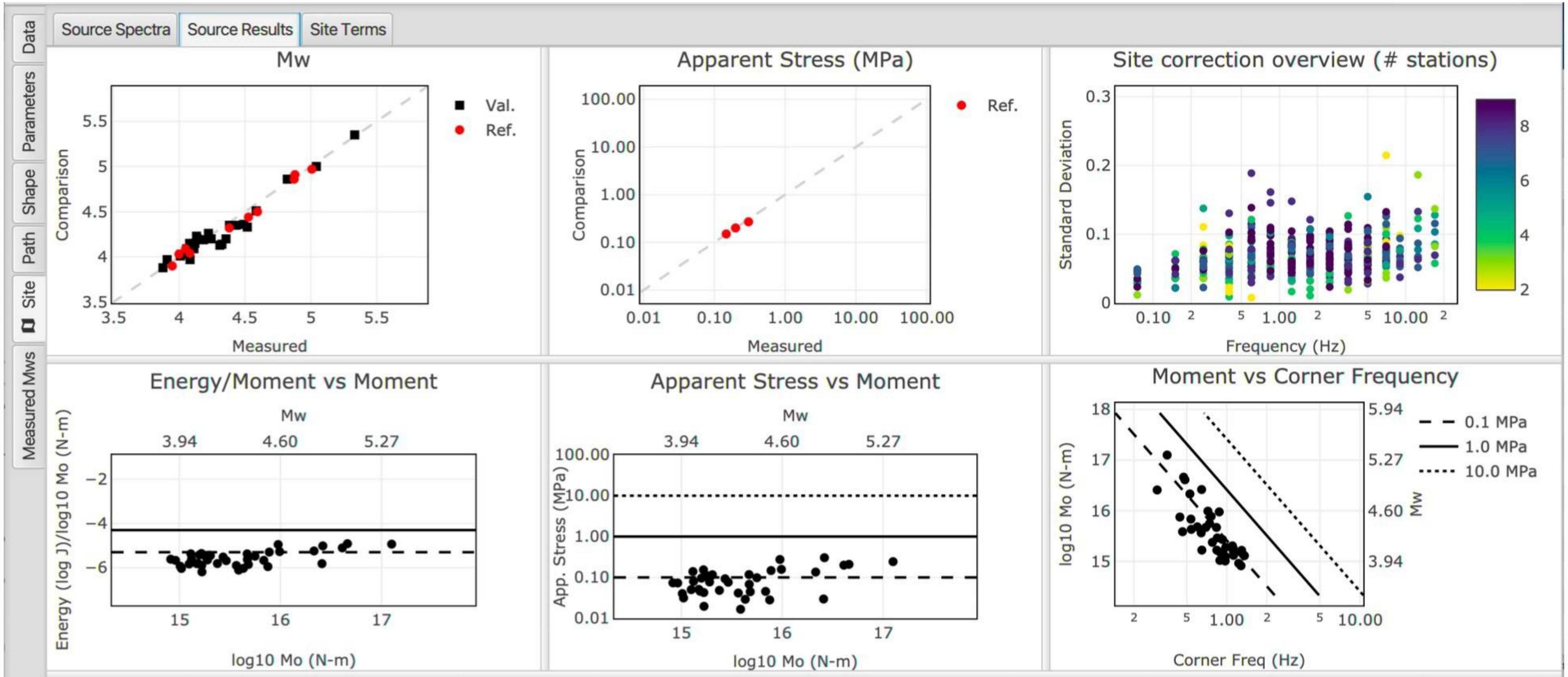
Path correction parameters to minimize interstation scatter

- Path correction parameters that minimize interstation scatter

- Quality control is based on amplitude differences between station pairs



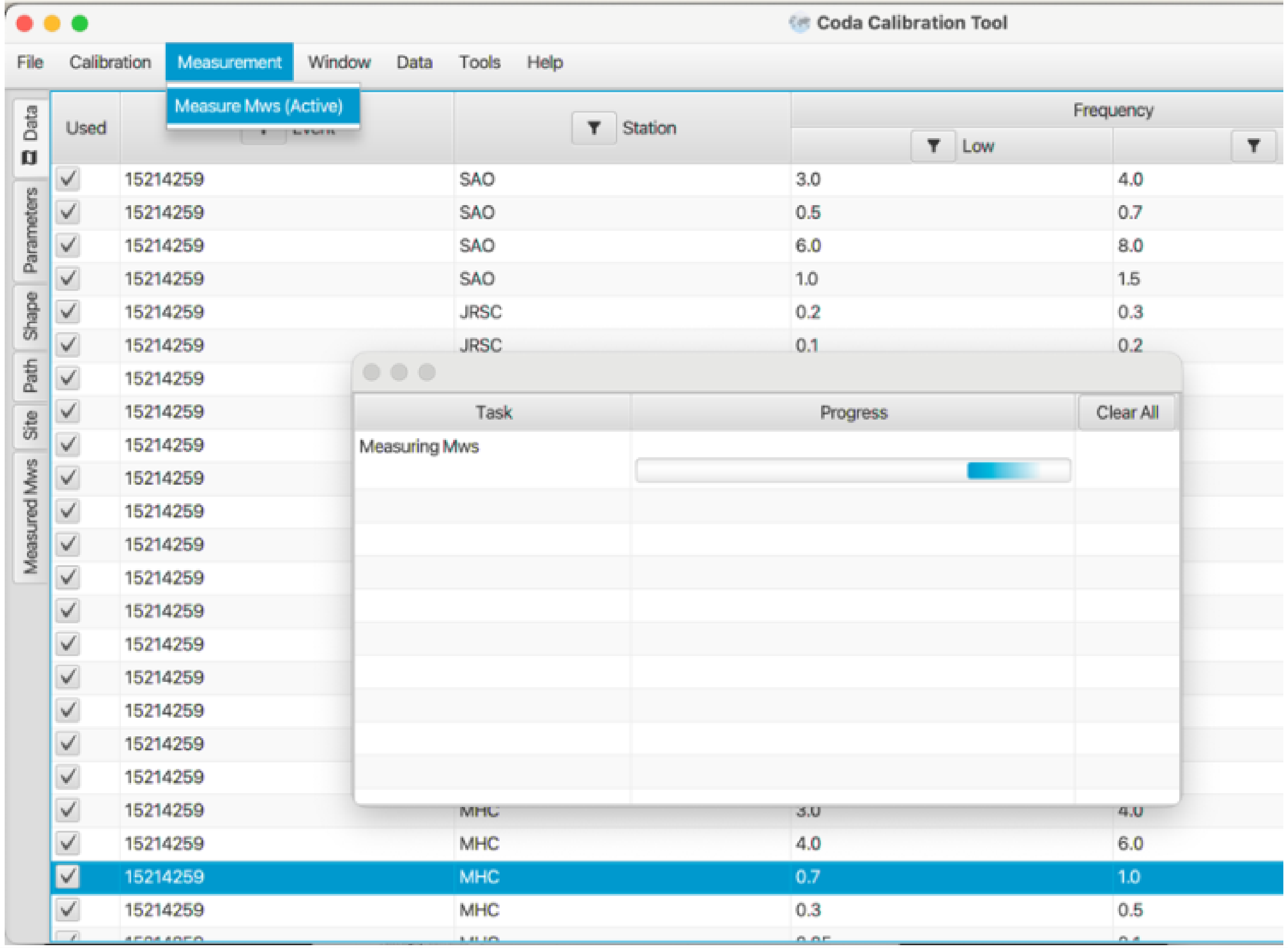
CCT Summary Plots



Evid	Date	Mw	Me	ObsTotalEnergy	Obs/TotalObs	ObsAppStress	App.Stress (MPa)	Ref Mw	Ref Stress	Fc (Hz)
30103999	1996-04-19T0...	4.8739	3.8635	10.5953	0.9286	0.09	0.0297	4.86		0.2994
30106749	1996-05-21T2...	4.5949	3.9463	10.7195	0.8542	0.186	0.1577	4.50		0.7203

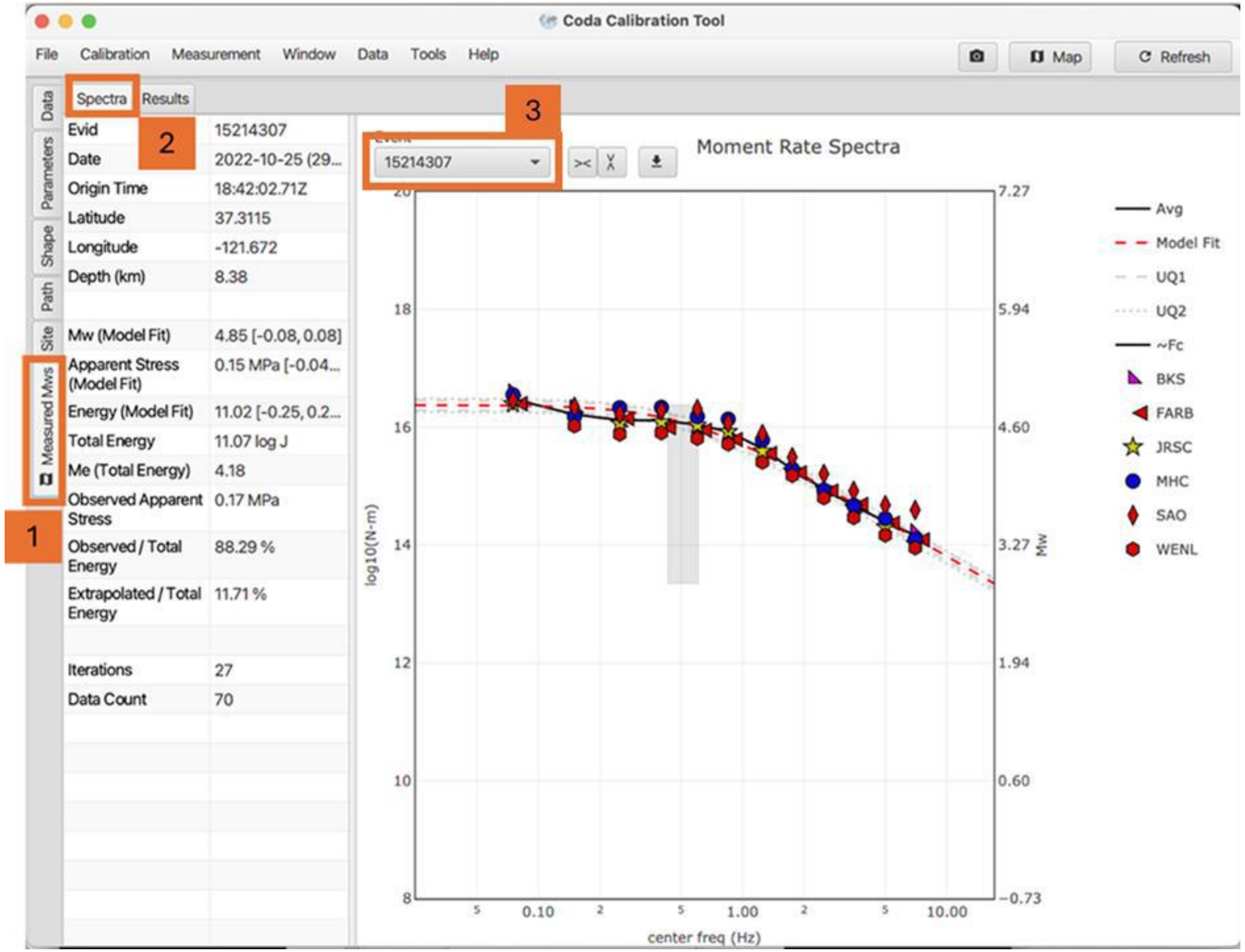
Estimating Mw's after Calibration

- Create and then load the envelopes for the new events.
- Load the previously created calibration and then click Measure Mws. The code will automatically pick the envelopes and estimate Mws.



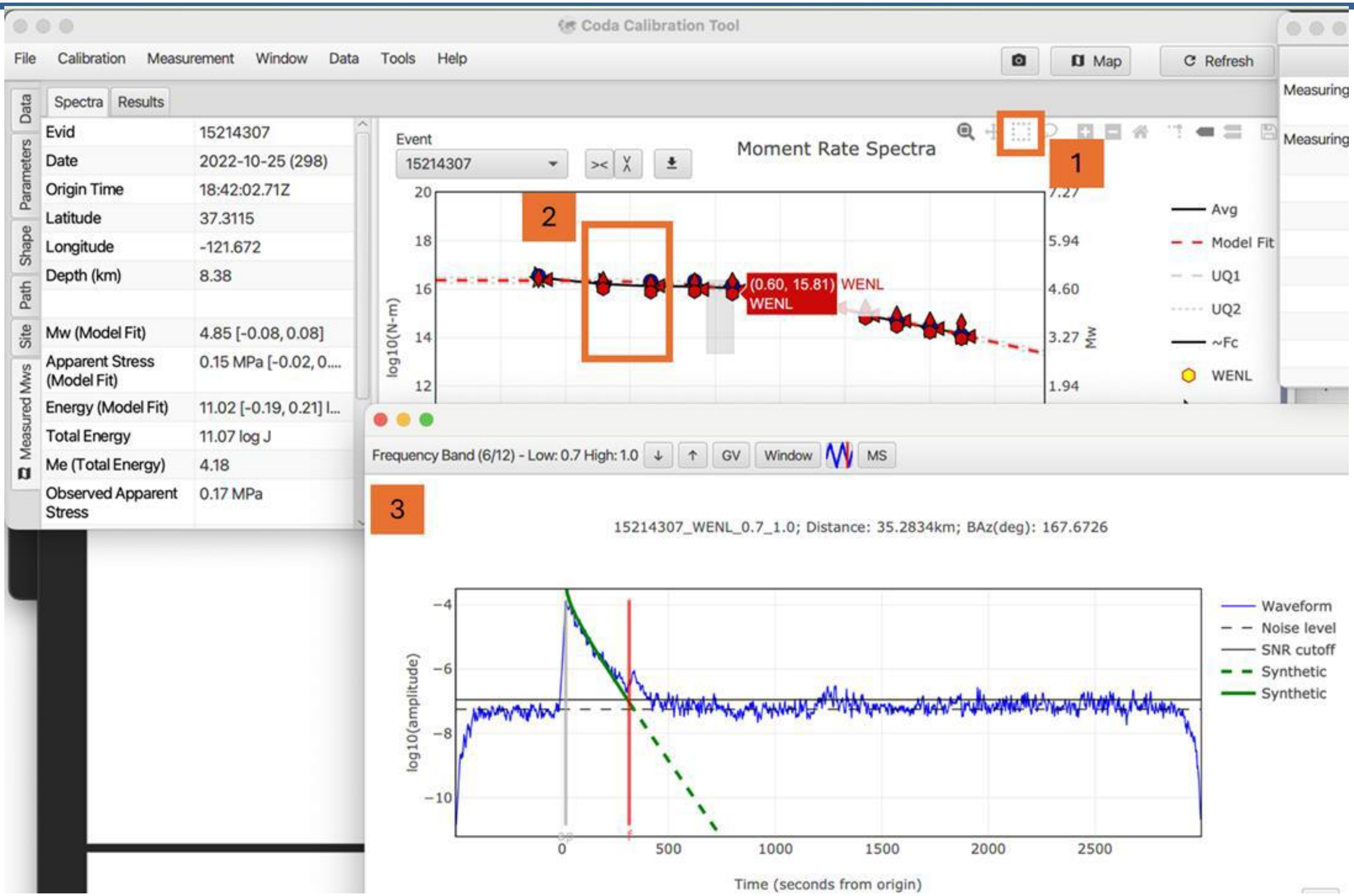
Estimating Mw's after Calibration

- You should always examine the spectra to make sure it looks realistic.



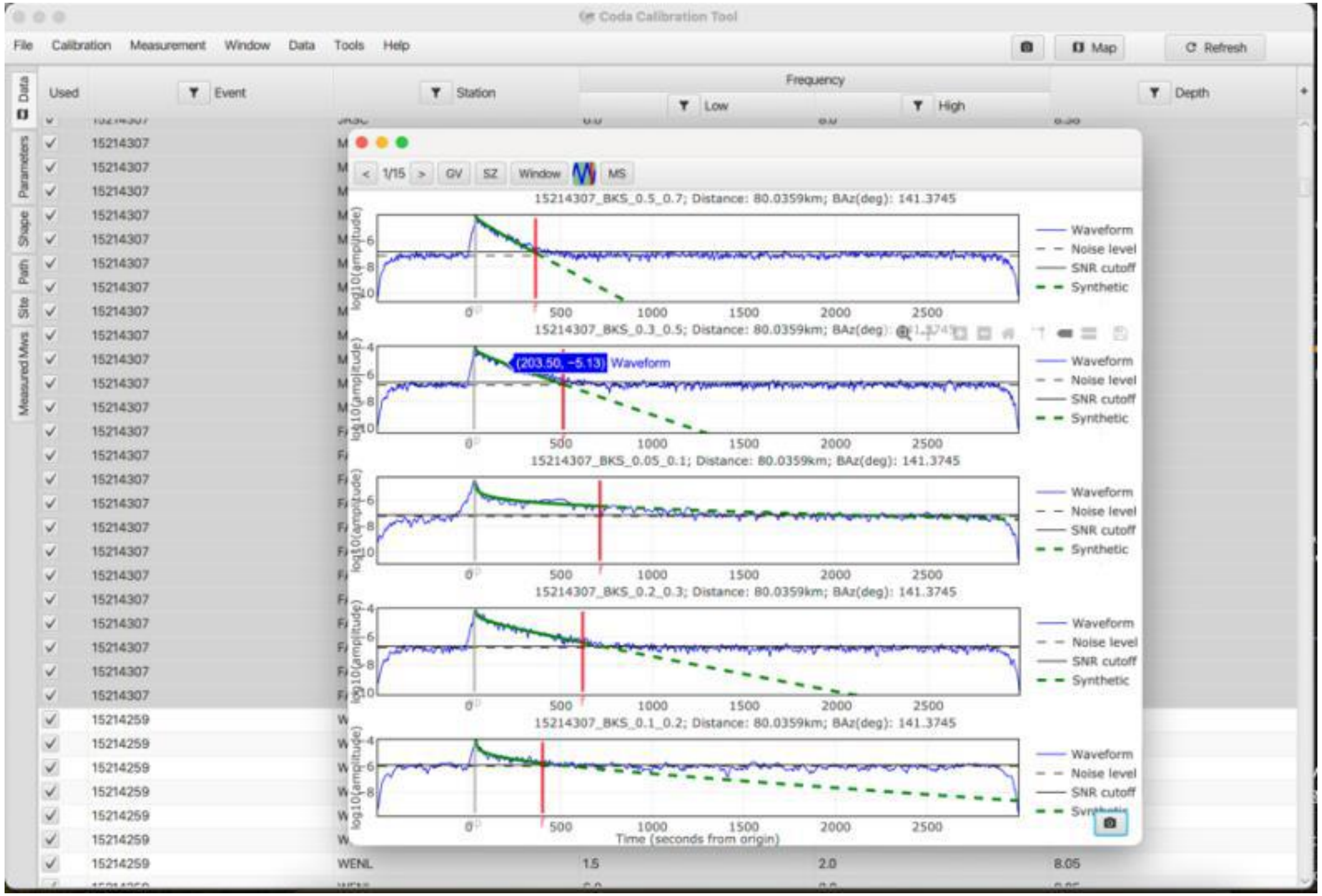
Estimating Mw's after Calibration

- If something does not look right you can select the measurement points and examine the picked envelopes associated with them.



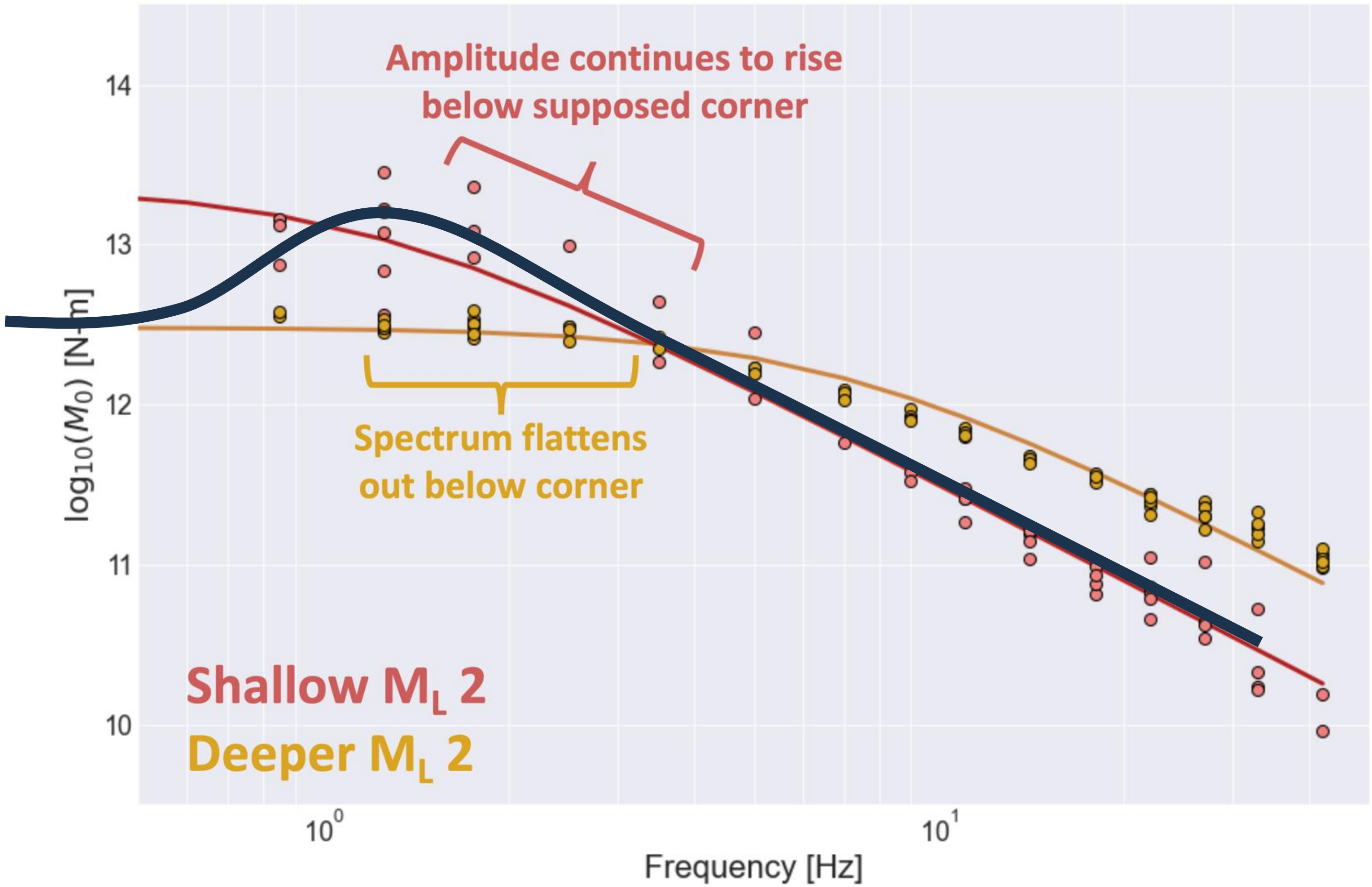
Estimating Mw's after Calibration

- This can be done for single measurements or many



Issues you might encounter: Shallow Events

- Shallow events coda has a distinctive bump that causes it to rise at low frequencies. Eventually it should return to normal amplitude level.
- If you lack enough low frequency coda estimates you will get higher magnitude estimates



Summary and Uses of CCT

- Coda calibration and measurement tools allows for robust Mw and source spectra measurements, even for earthquakes too small to waveform model and smaller than any in your reference ecents.
- Coda can get absolute seismic measurements from DAS and other uncalibrated data
- Coda can identify unusually shallow depth events
- CCT can improve our understanding about source characteristics
  - New coda envelope ratio tool (CERT) to allow exploration of ratio techniques to get at source characteristics
- Application of coda techniques to determine source characteristics – spectra, energy, apparent stress, depth, are in early days and an exciting area of future work

Open-Source Coda Calibration Tool available through GitHub

You can access the Coda Calibration Tool (CCT) here:

Required Java: https://adoptium.net/
CCT Tutorial: https://software.llnl.gov/coda-calibration-tool/
CCT Code: https://github.com/LLNL/coda-calibration-tool

This tool is under active development and we welcome feedback ^.^
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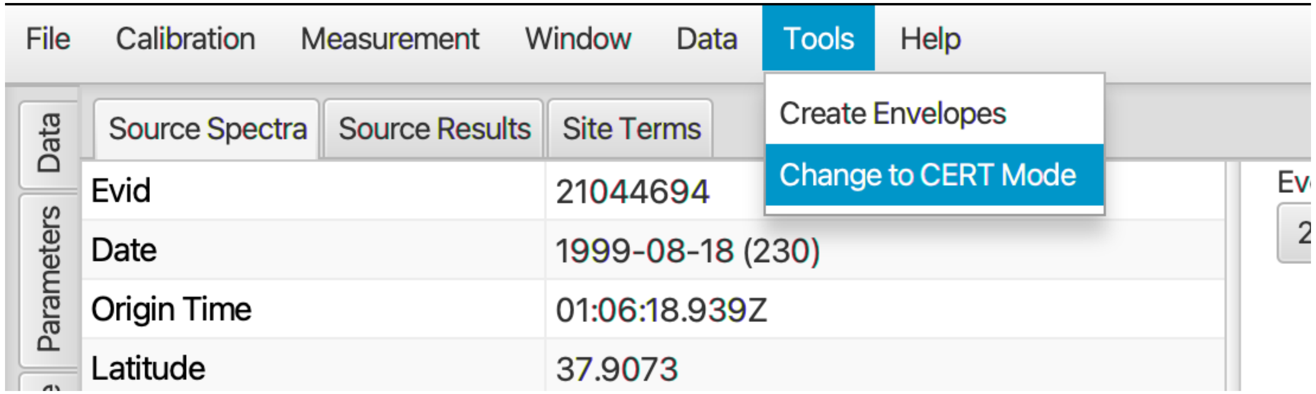
Extra Slides

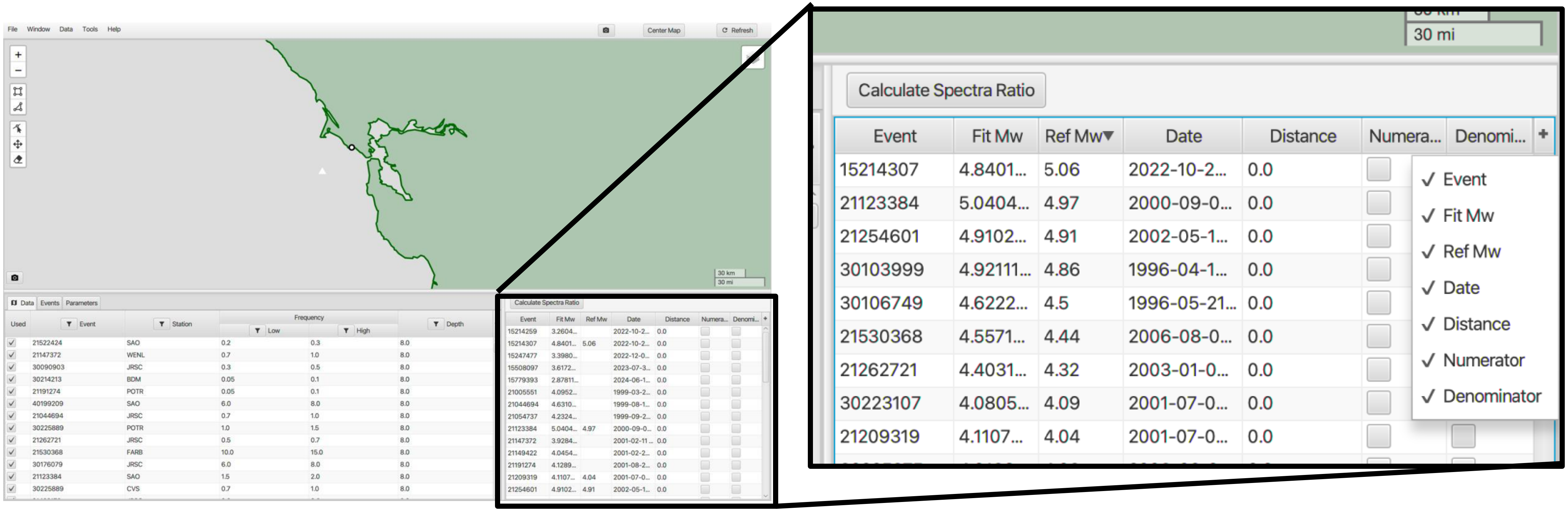
Coda Ratios: Coda Envelope Ratio Tool (CERT)

- Coda Envelope Ratios is very similar to normal spectral ratios except the spectra we will be ratioing comes from coda. It can often be more forgiving in EGF selection that direct wave coda ratio analysis
- Newly added to the tool is in beta coda envelope ratio tool.



Coda Ratios: Coda Envelope Ratio Tool (CERT)

- It will bring up a list of events sorted by either estimated magnitude by CCT tool or provided Mws



Coda Ratios: Coda Envelope Ratio Tool (CERT)

- You can select your numerator event and then estimate the distance of all other events from it to start selecting the denominator event.

Calculate Spectra Ratio

Event	Fit Mw	Ref Mw ▼	Distance	Numerator	Denominator
15214307	4.84011110...	5.06	0.0	✓	
21123384	5.0404967...	4.97	0.0		
21254601	4.9102377...	4.91	0.0		
30103999	4.92111912...	4.86	0.0		
30106749	4.6222172...	4.5	0.0		
21530368	4.5571907...	4.44	0.0		
21262721	4.4031801...	4.32	0.0		
30223107	4.0805481...	4.09	0.0		

Set Rows As Numerator
Set Rows As Denominator
De-Select Rows
Calculate Distance to This Event

Calculate Spectra Ratio

Event	Fit Mw	Ref Mw	Distance ▲	Numerator	Denominator
15214307	4.84011110...	5.06	0.0	✓	
15214259	3.2604199...		0.2955939494...		
15247477	3.3980427...		2.11173606905...		
21149422	4.0454449...		3.35121744963...		
15779393	2.87811751...		6.8020557794...		
30106749	4.6222172...	4.5	6.93411510214...		
15508097	3.61722414...		7.0769930893...		
40204628	5.3481025...		16.2682447710...		

Coda Ratios: Coda Envelope Ratio Tool (CERT)

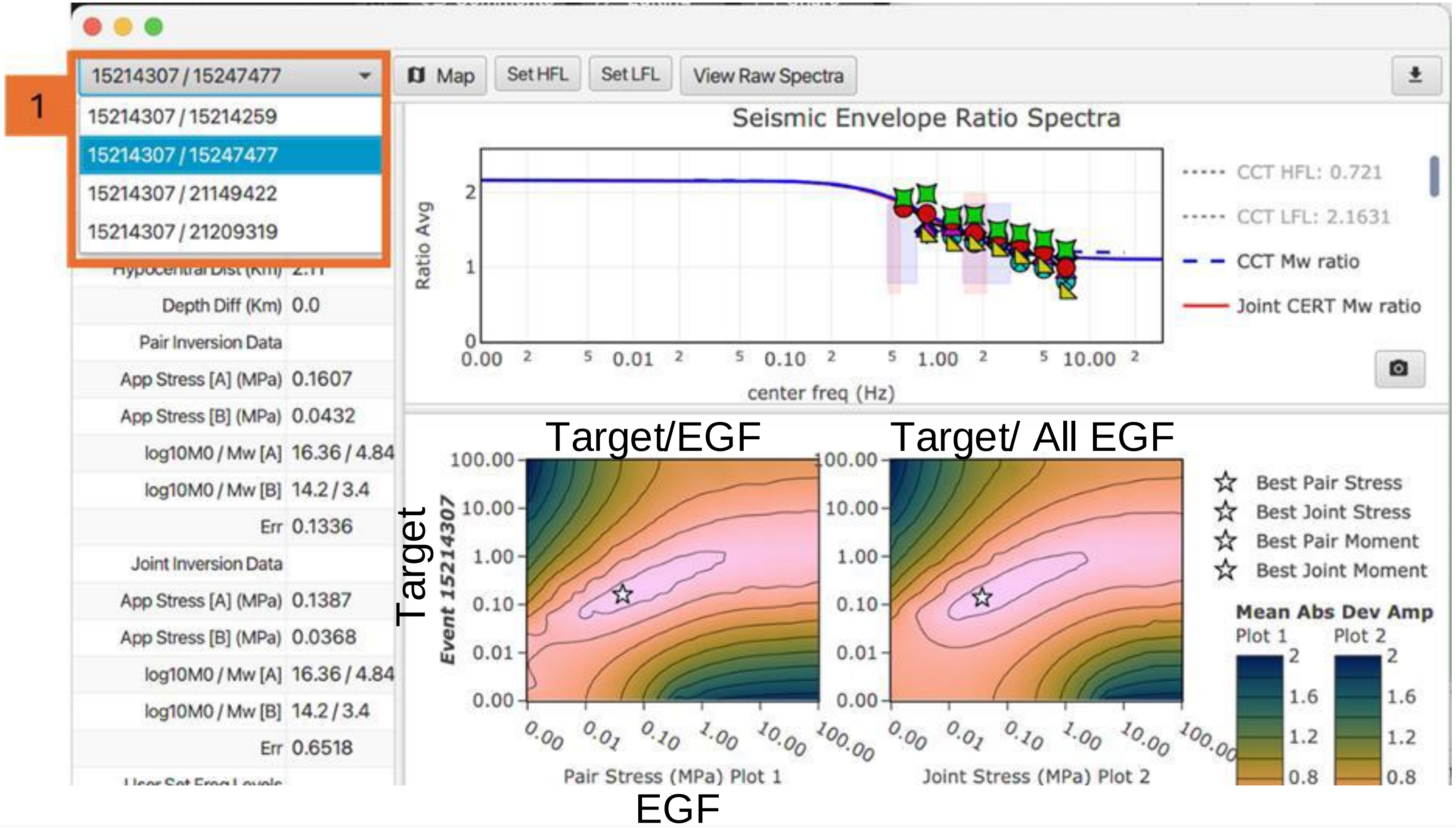
- For example here we select the Alumn Rock event and then 3 close aftershocks.

Calculate Spectra Ratio

Event	Fit Mw	Ref Mw	Distance ▲	Numerator	Denominator
15214307	4.84011110...	5.06	0.0	✓	
15214259	3.2604199...		0.2955939494...		✓
15247477	3.3980427...		2.11173606905...		✓
21149422	4.0454449...		3.35121744963...		✓
15779393	2.87811751...		6.8020557794...		
30106749	4.6222172...	4.5	6.93411510214...		
15508097	3.61722414...		7.0769930893...		
40204628	5.3481025...		16.2682447710...		

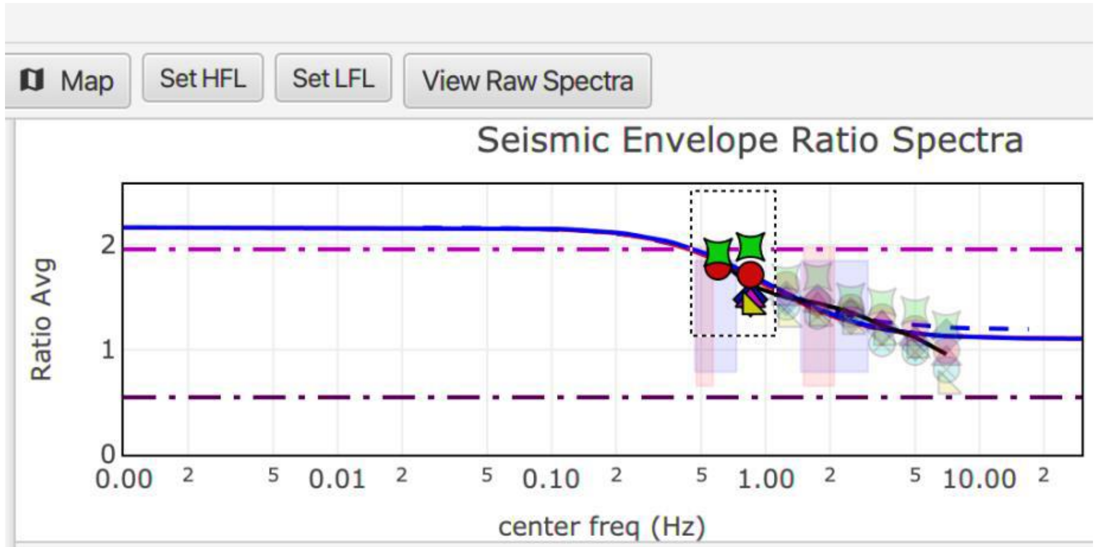
Coda Ratios: Coda Envelope Ratio Tool (CERT)

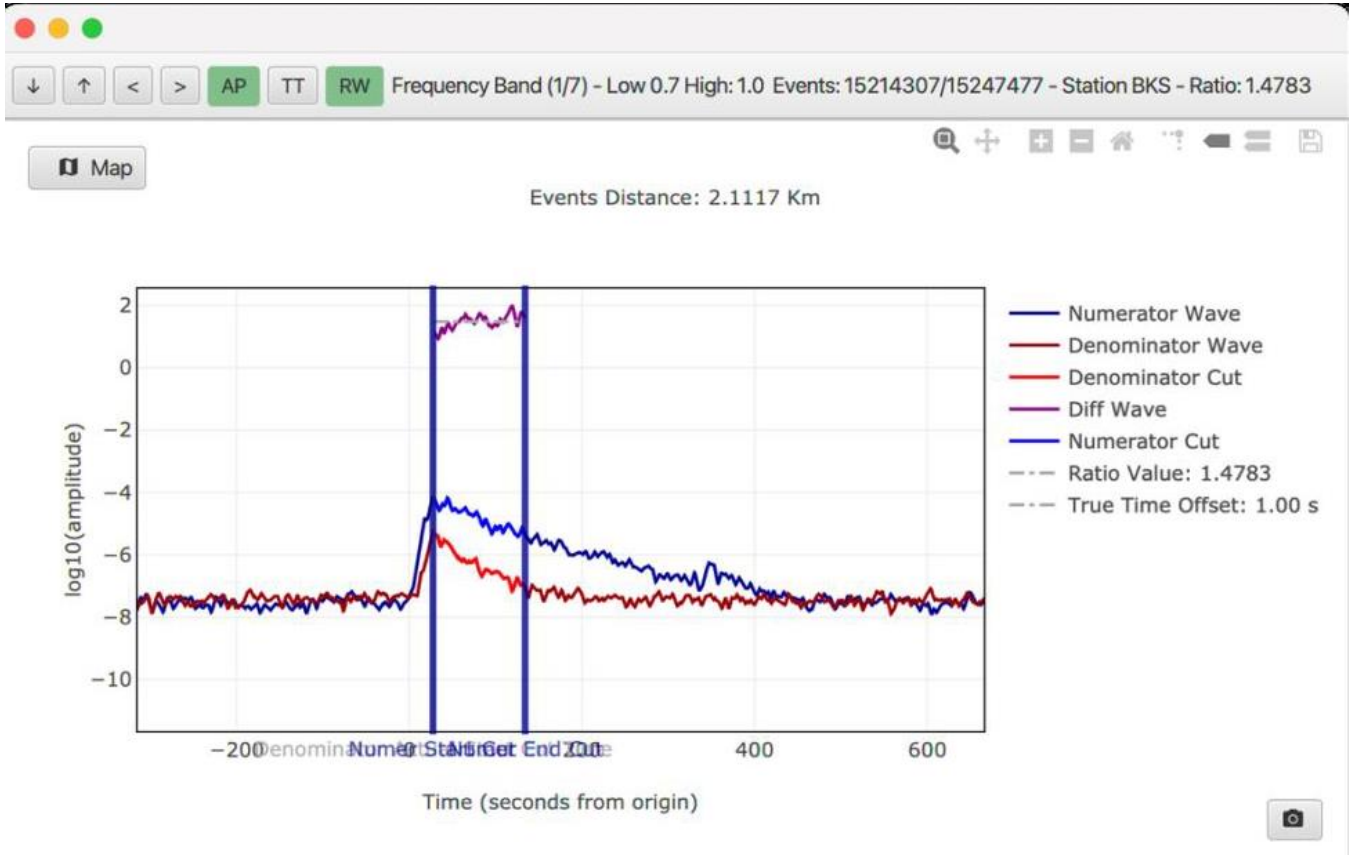
- The EGFs lack low frequencies but the user can go back an add those in to improve the estimate.



Coda Ratios: Coda Envelope Ratio Tool (CERT)

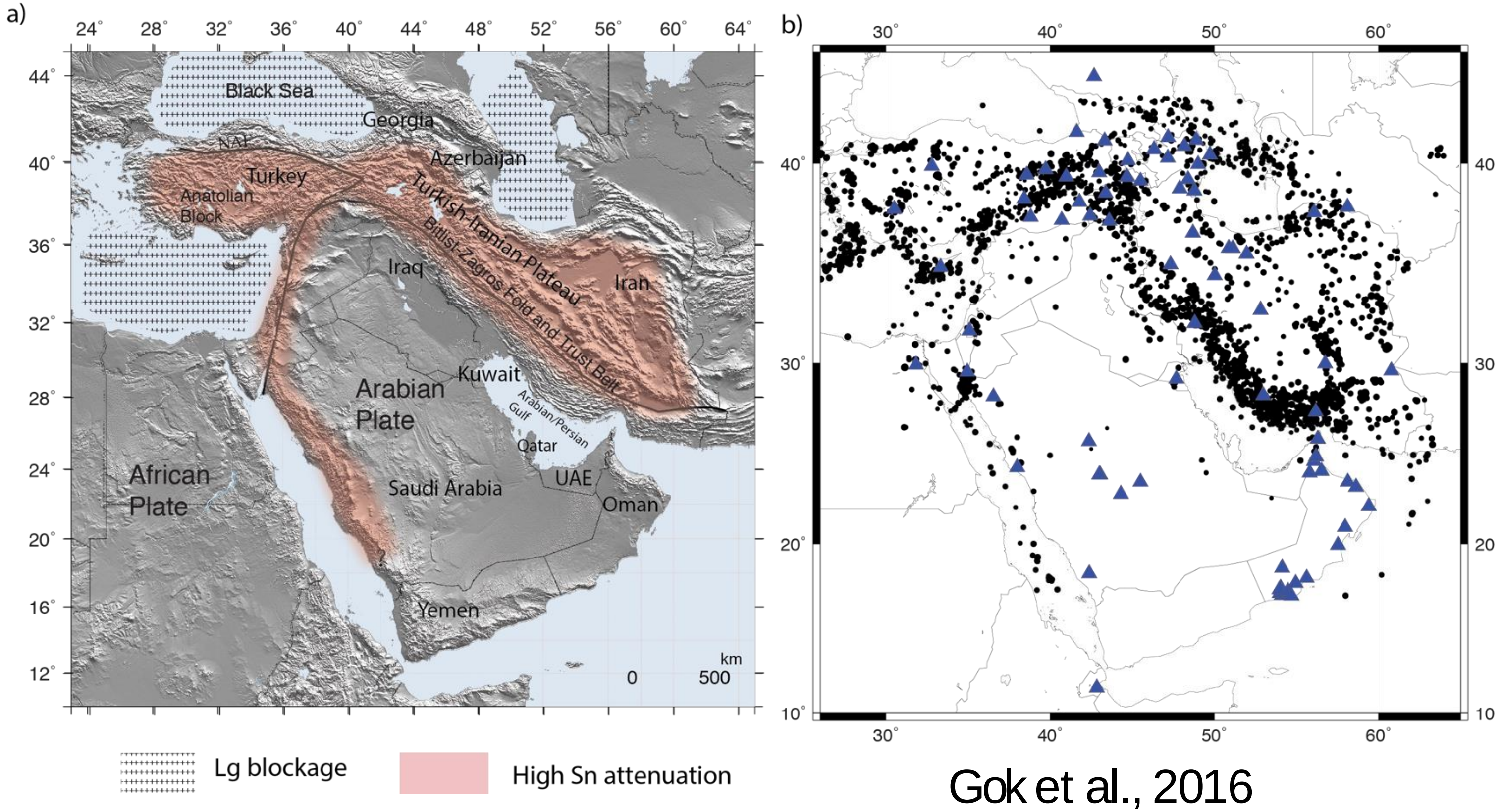
- Just like in the CCT tool the user can select and examine the envlopes





Example Study: Middle East Coda Calibration Project 2,500 events 70 stations

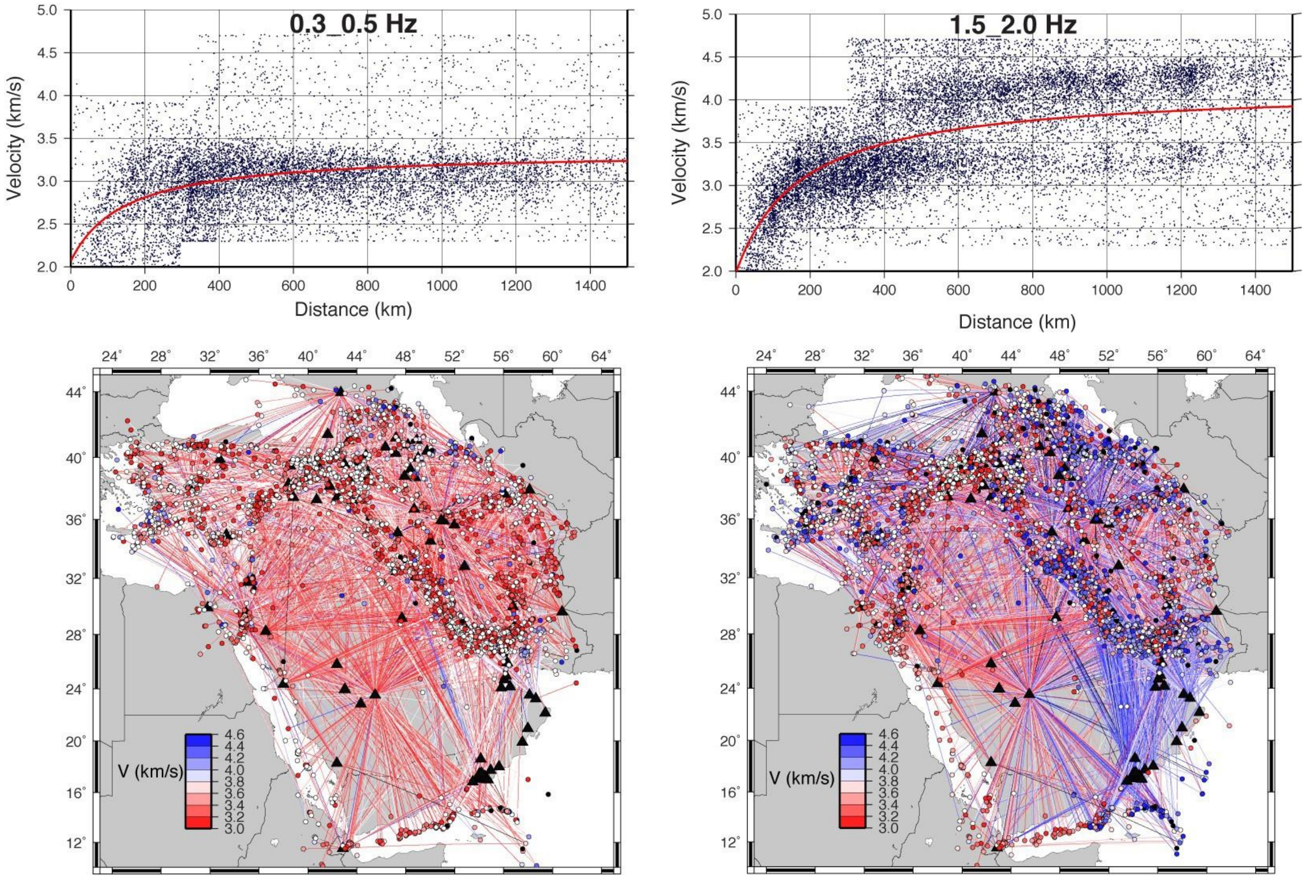
- Complex tectonics where you have regions of Lg blockage and high Sn attenuation.
- This study showed that 1D coda-derived magnitudes provide great stability, due to their averaging nature at frequencies of 0.7 Hz and lower, and thus are applicable for events Mw ≥ ~4.0 for this region



Gok et al., 2016

Coda Envelopes and Peak Velocities in the Middle East

- Regional S-wave characteristics influence the coda envelope calibrations.
- Coda start times show variability at higher frequencies depending on the structural heterogeneity in the calibrated region.



from Gok et al., 2016