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Case study: measurement of Q and cumulative attenuation from VSP data

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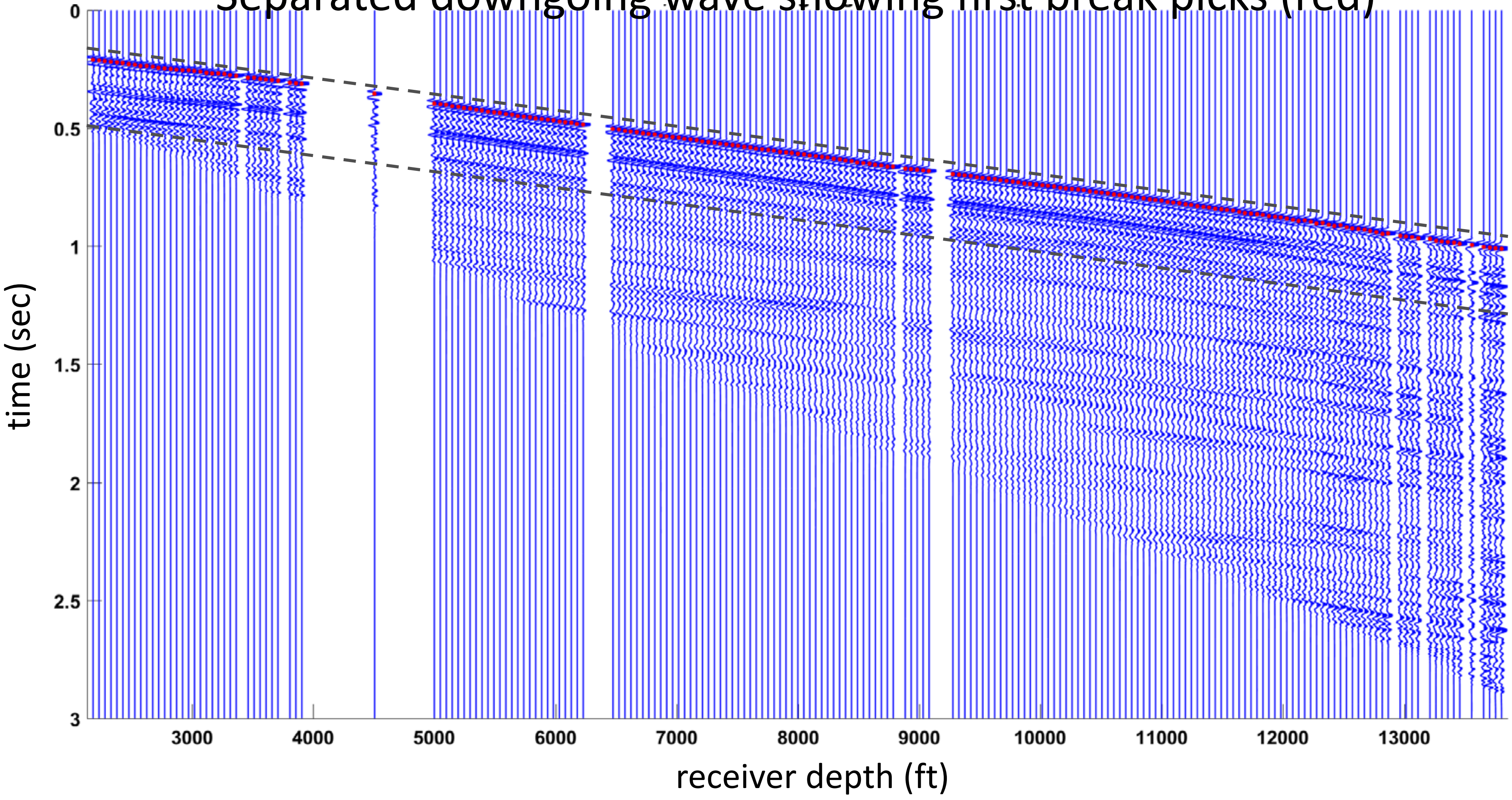
Downgoing wave

Separated downgoing wave showing first break picks (red)



Extracted analysis ribbon

A 300ms window flattened on the first break.

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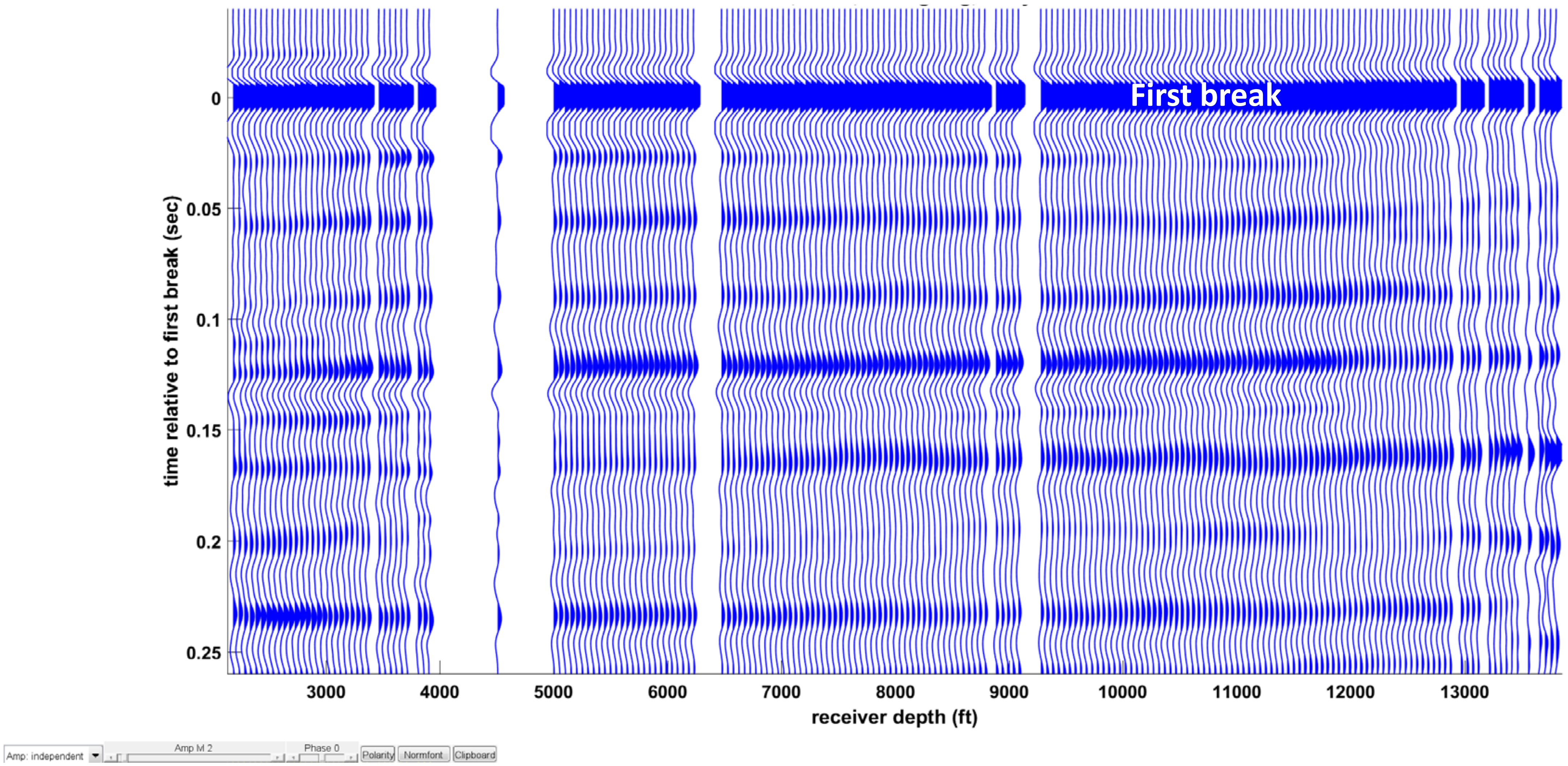
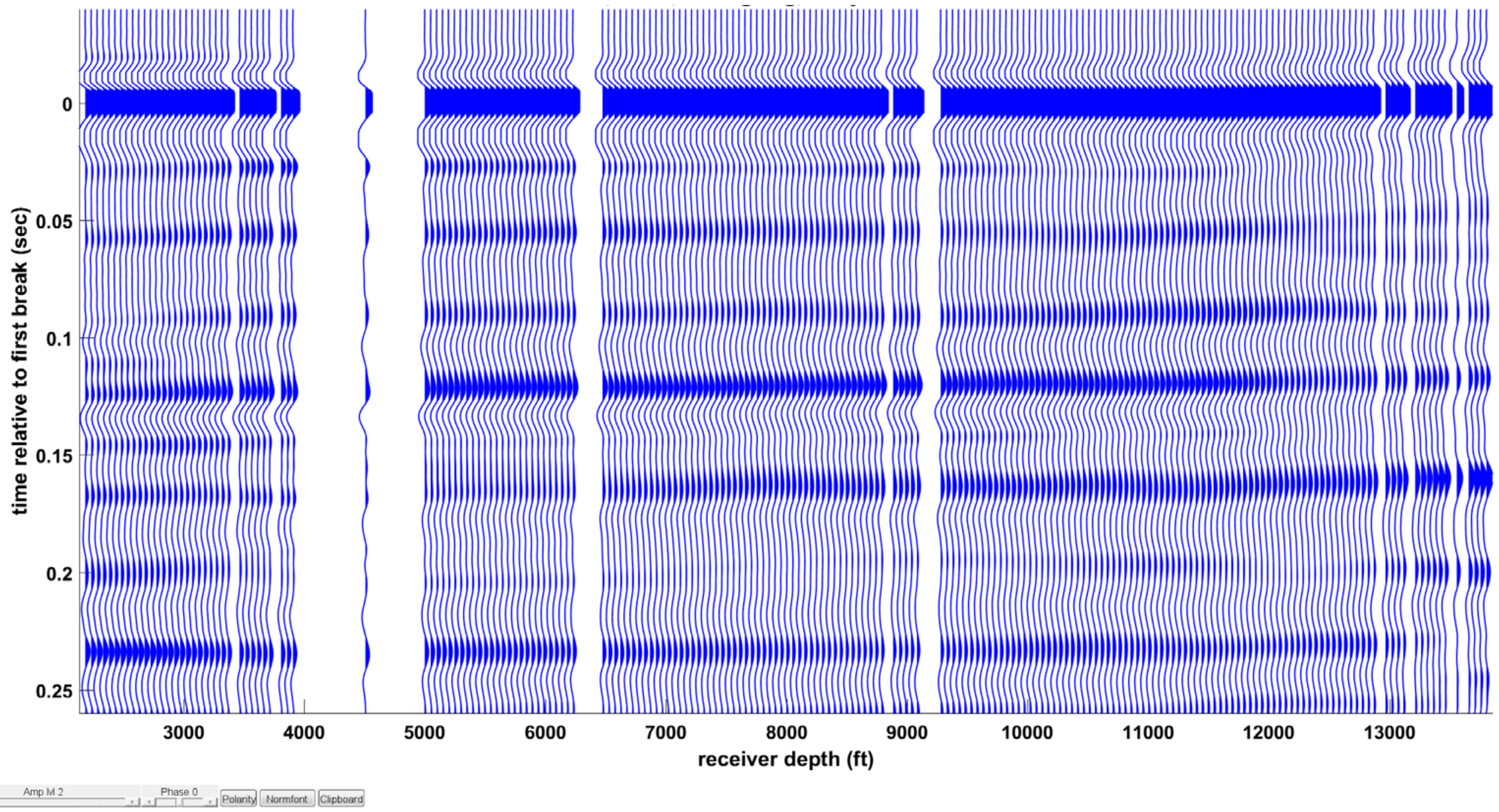
Analysis ribbon



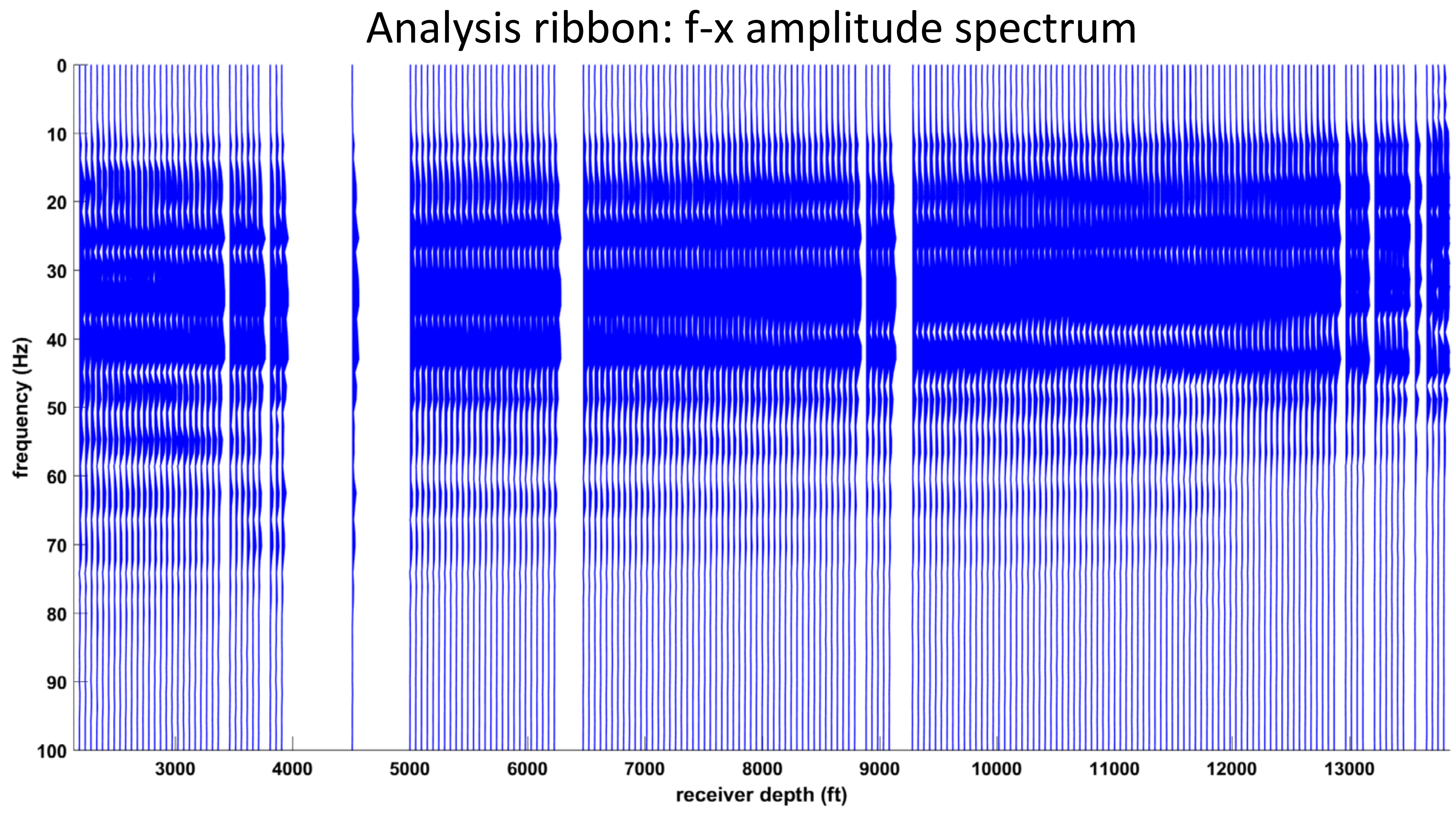
Extracted analysis ribbon, spatially averaged with delz=400

After a spatial mix. Essentially each trace is the average of neighboring traces over +/- 400m

Analysis ribbon after spatial mix



f-x amplitude spectrum of analysis ribbon



f-x amplitude spectrum of analysis ribbon, delz=400

After a spatial mix. Essentially each trace is the average of neighboring traces over +/- 400m

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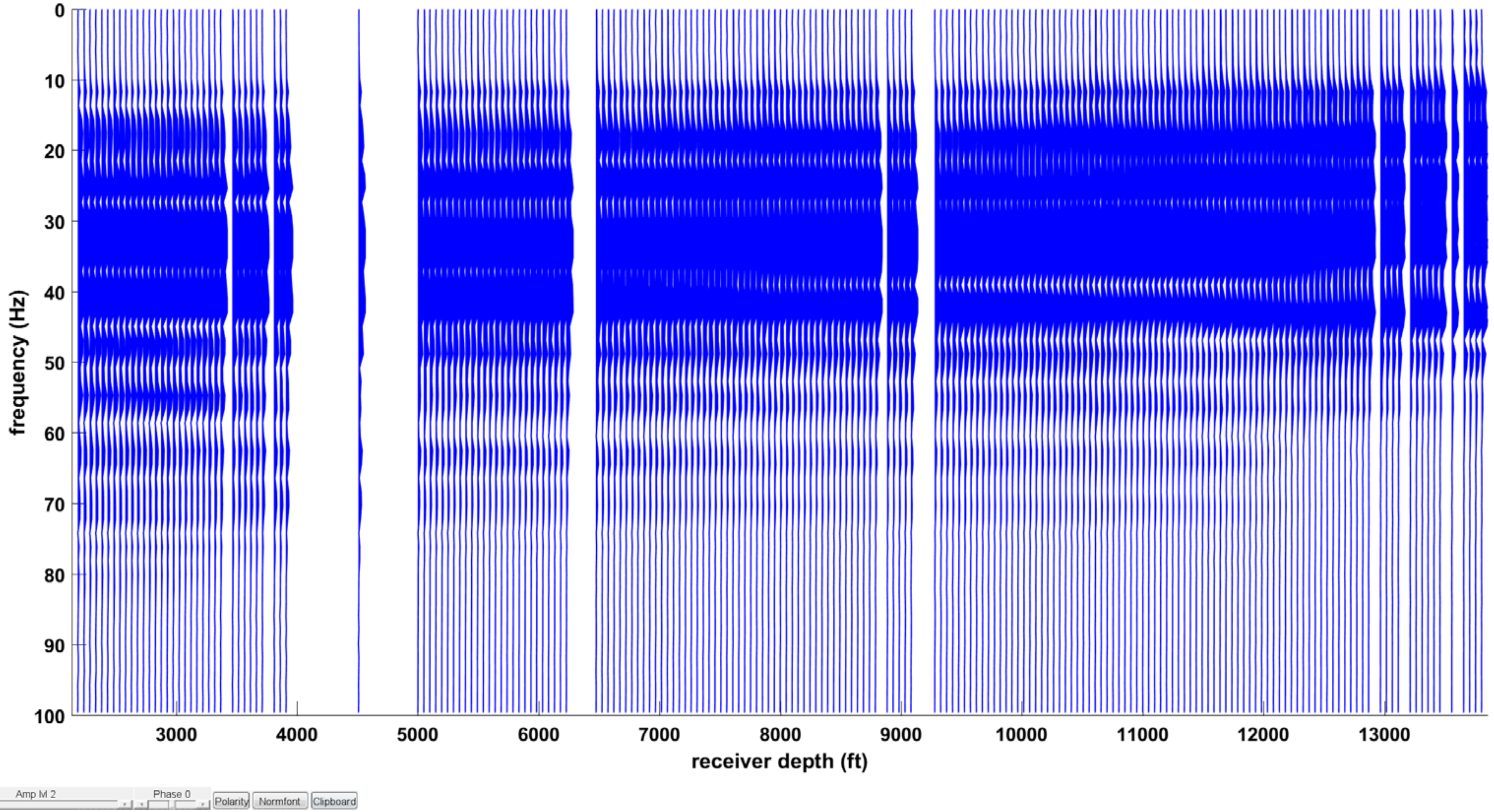
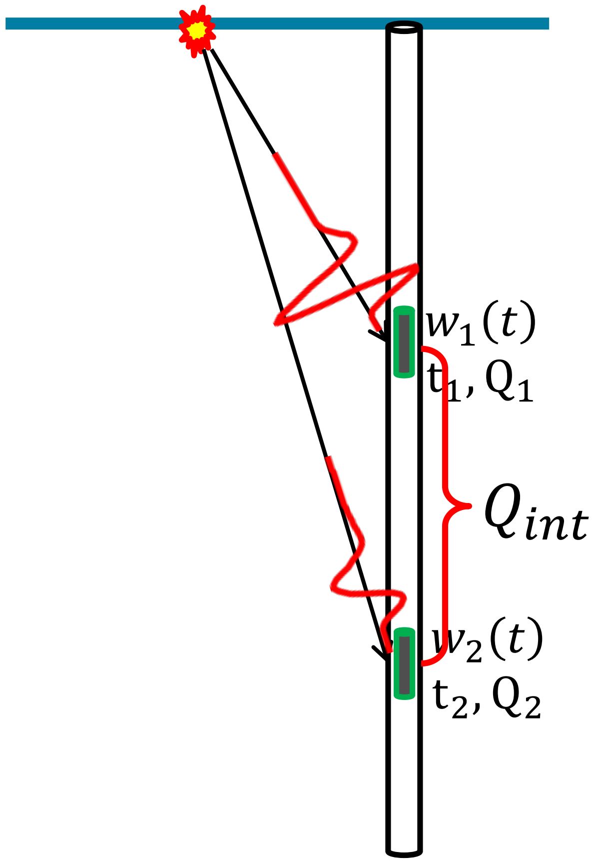
Analysis ribbon after spatial mix: f-x amplitude spectrum



Spectral-ratio method of Q estimation

This is the most commonly used method



Form the log-spectral-ratio

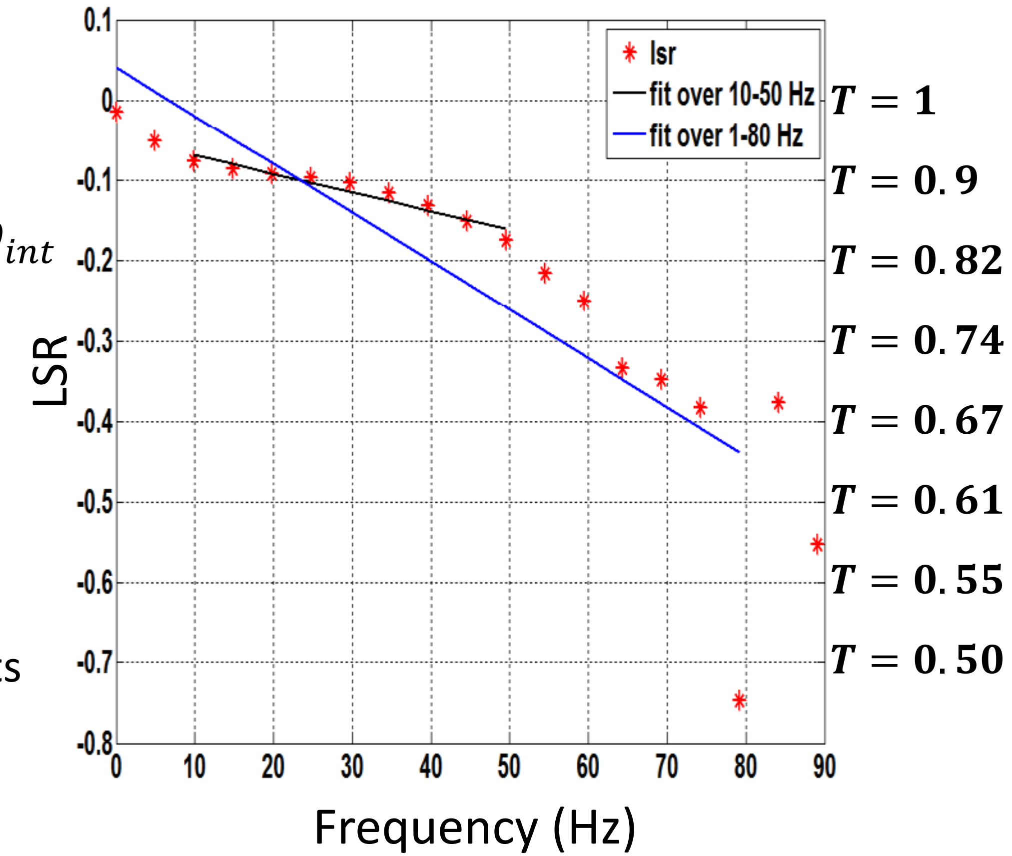
$$LSR = \log\frac{A_2}{A_1} = \log T - \pi f(t_2 - t_1)/Q_{int}$$

T = transmission coefficient

A_1, A_2 = amplitude spectra

Strategy:

1. Form *LSR*
2. Fit a 1st order polynomial
3. Slope predicts Q_{int}, intercept predicts T.

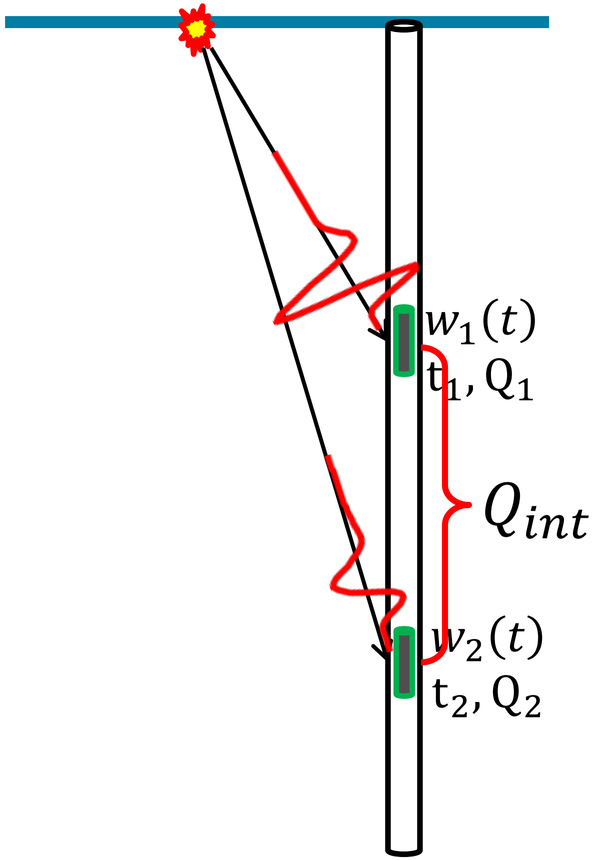


Predicted values for Q and T depend on the frequency range of the fit.

Dominant frequency method of Q estimation

This is new. It has the virtue of not needing a division.

Strategy: Find the forward Q filter that when applied to w_1 reduces the dominant frequency to that of w_2.



Compute the dominant frequency at both levels from

$f_{dom1} = \frac{\sum_k f_k A_{1k}^2}{\sum_k A_{1k}^2}$ and similarly for f_{dom2}

$f_k =$ the k^{th} frequency

$A_{1k}, A_{2k} =$ amplitude spectra at that frequency

Note the use of Power Spectra.

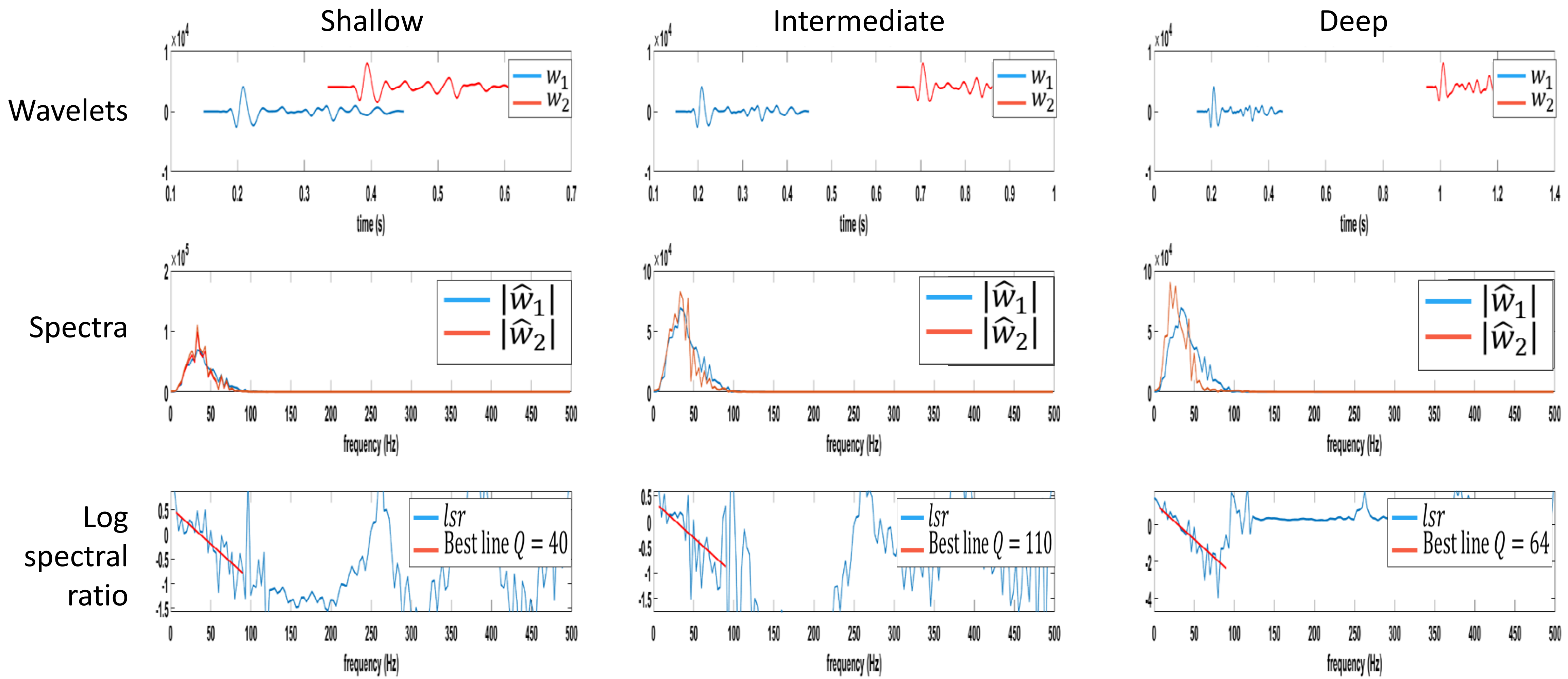
Strategy:

1. Assume $Q = Q_j$
2. Calculate: $A'_{2k} = A_{1k} e^{-\pi f_k (t_2 - t_1)/Q_j}$

   and $f'_{dom2} = \frac{\sum_k f_k A'^2_{2k}}{\sum_k A'^2_{2k}}$
3. Search over $Q_j = 5,6,7 \; \ldots 300$ to find that Q such that f'_{dom2} comes closest to f_{dom2}
4. Algorithm also matches bandwidth.

Related to Quan and Harris, 1997, but significantly different.

Spectral-ratio analysis plots



Dominant-frequency analysis plots

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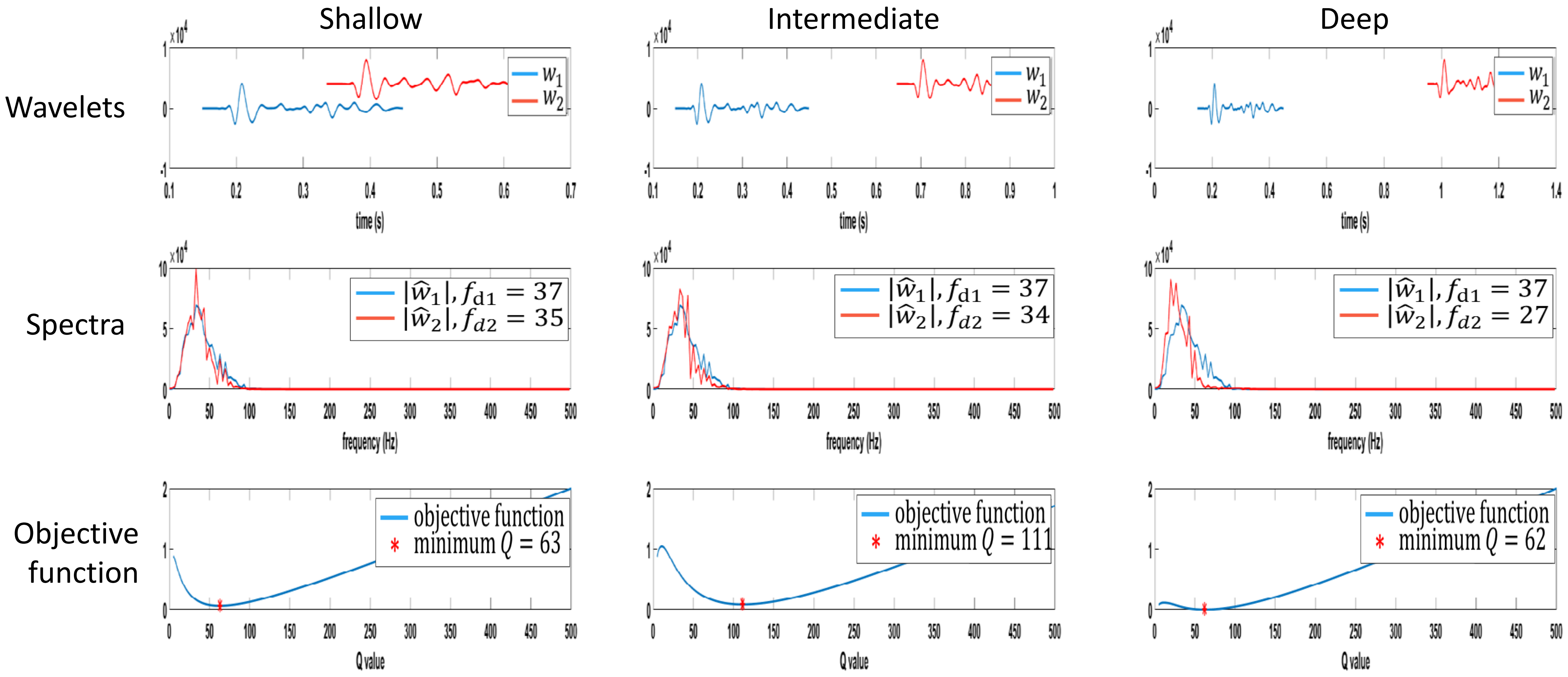


Cumulative attenuation or CA
after Hauge (1981)

Attenuation (Q^{-1}) consists of intrinsic and stratigraphic parts which combine to give total attenuation:

$$CA = \frac{\pi(t_2 - t_1)}{Q_{eff}} = \frac{\pi(t_2 - t_1)}{Q_{intrinsic}} + \frac{\pi(t_2 - t_1)}{Q_{strat}}$$

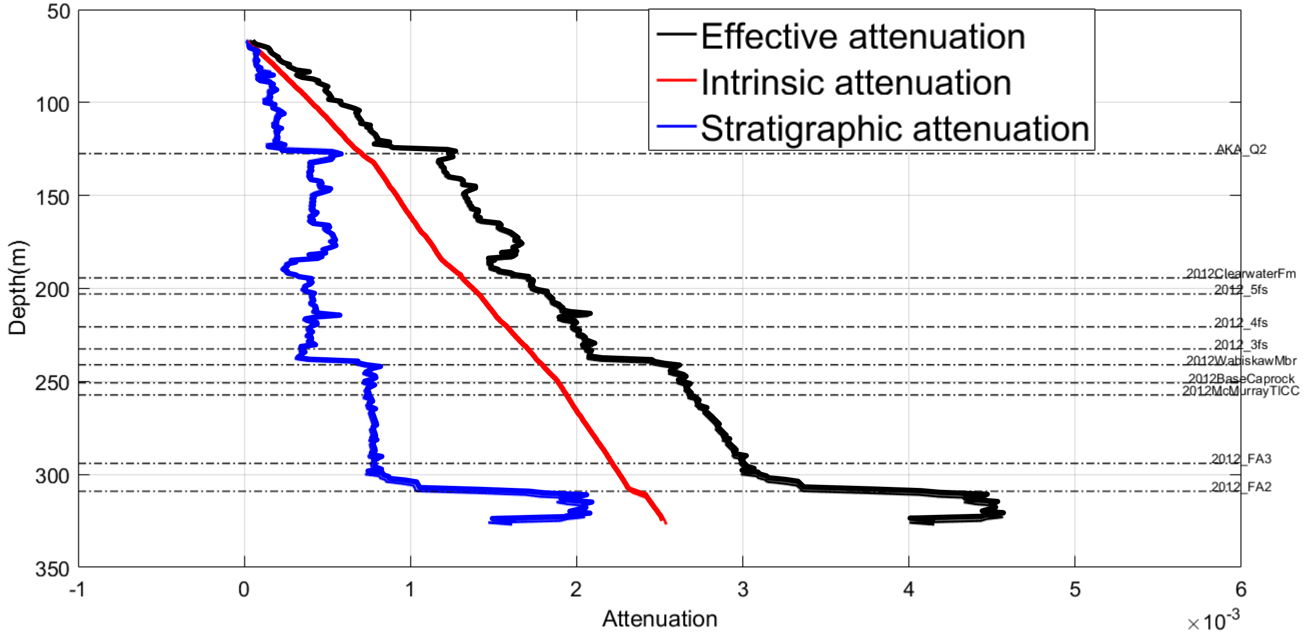
With time in the numerator, this is called *cumulative attenuation* or CA.

1. Effective attenuation is what is always measured.

2. Intrinsic attenuation is a rock or reservoir property. Monotonic.

3. Stratigraphic attenuation is an interference effect from short-path multiples (O'Doherty and Anstey 1971).

Cumulative attenuation from synthetic VSP

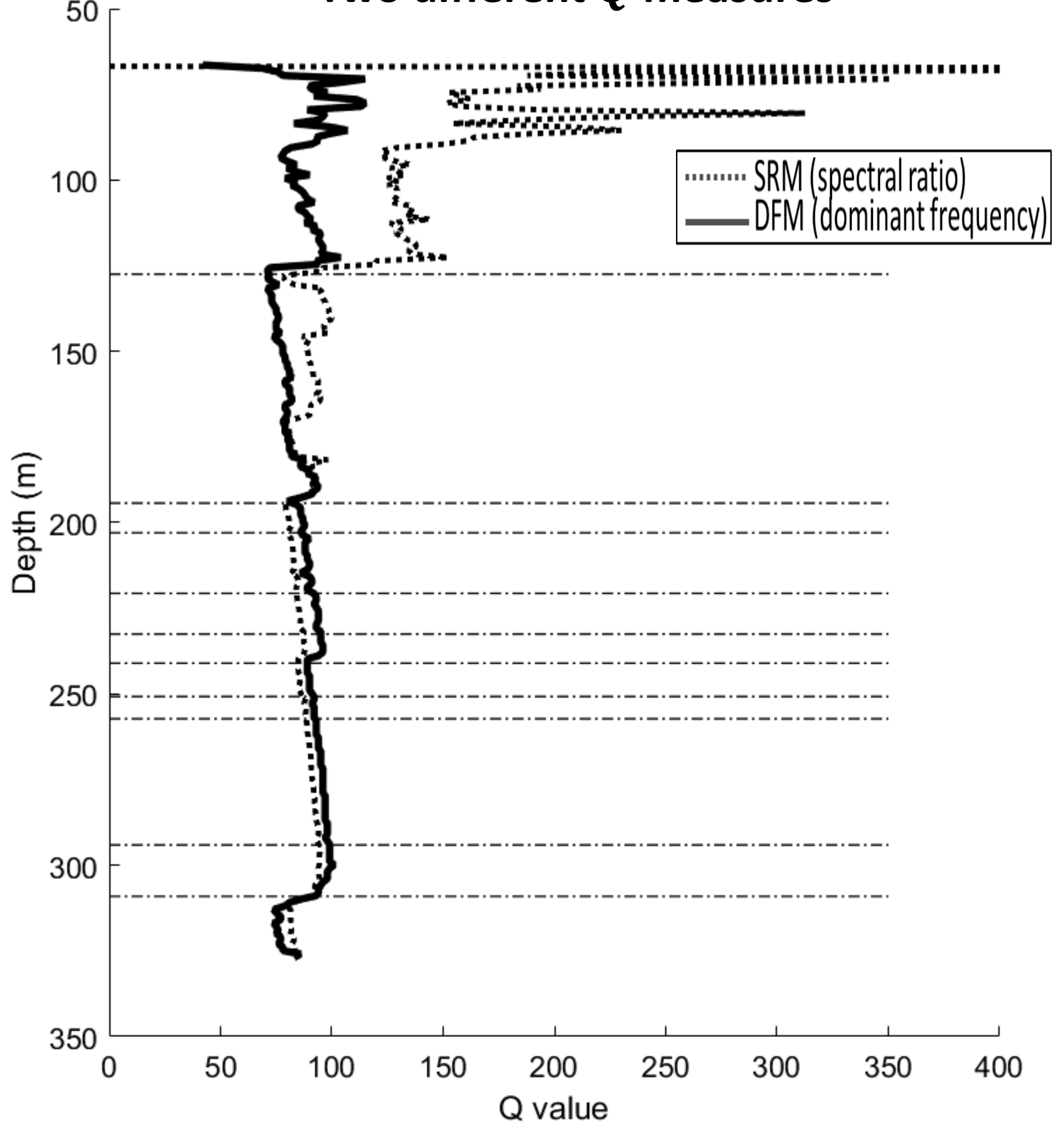


Q versus CA

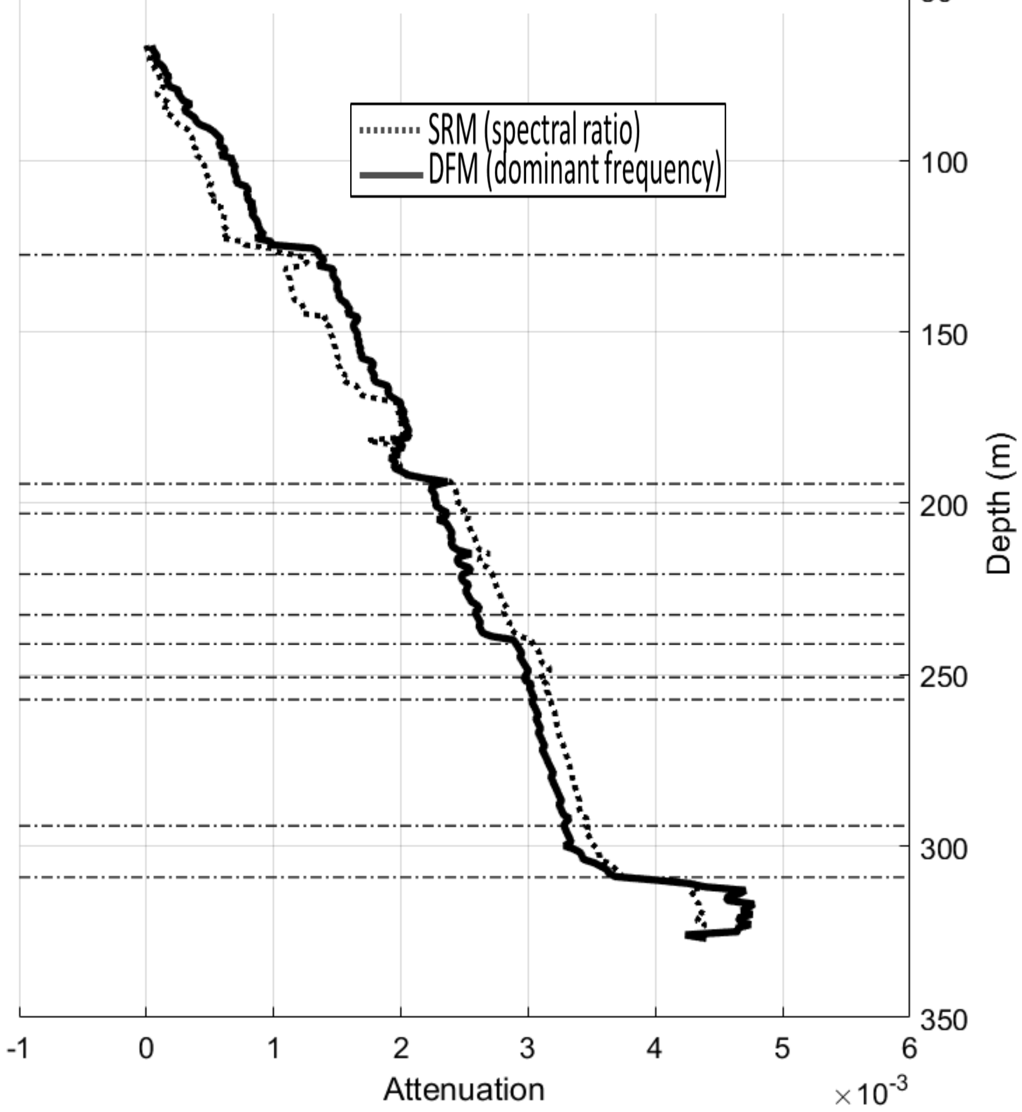
A test on a noise-free synthetic

SRM (spectral ratio)
DFM (dominant frequency)

Two different Q measures

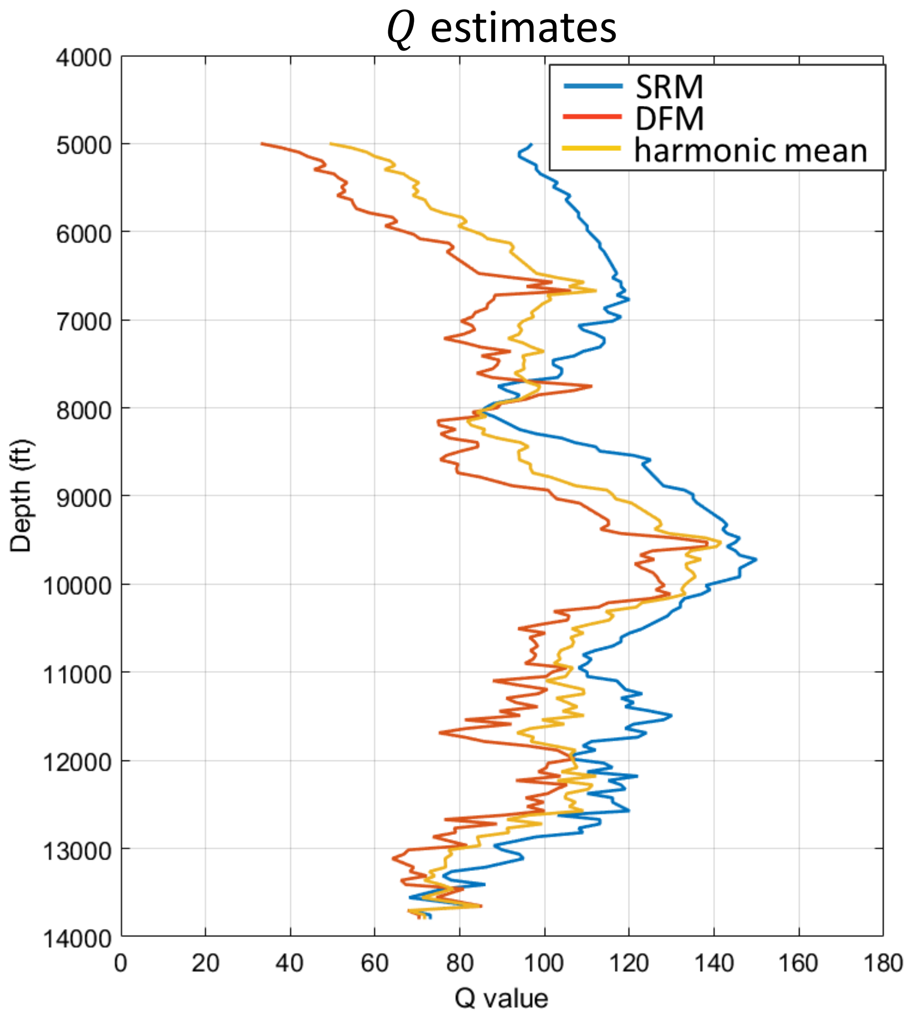


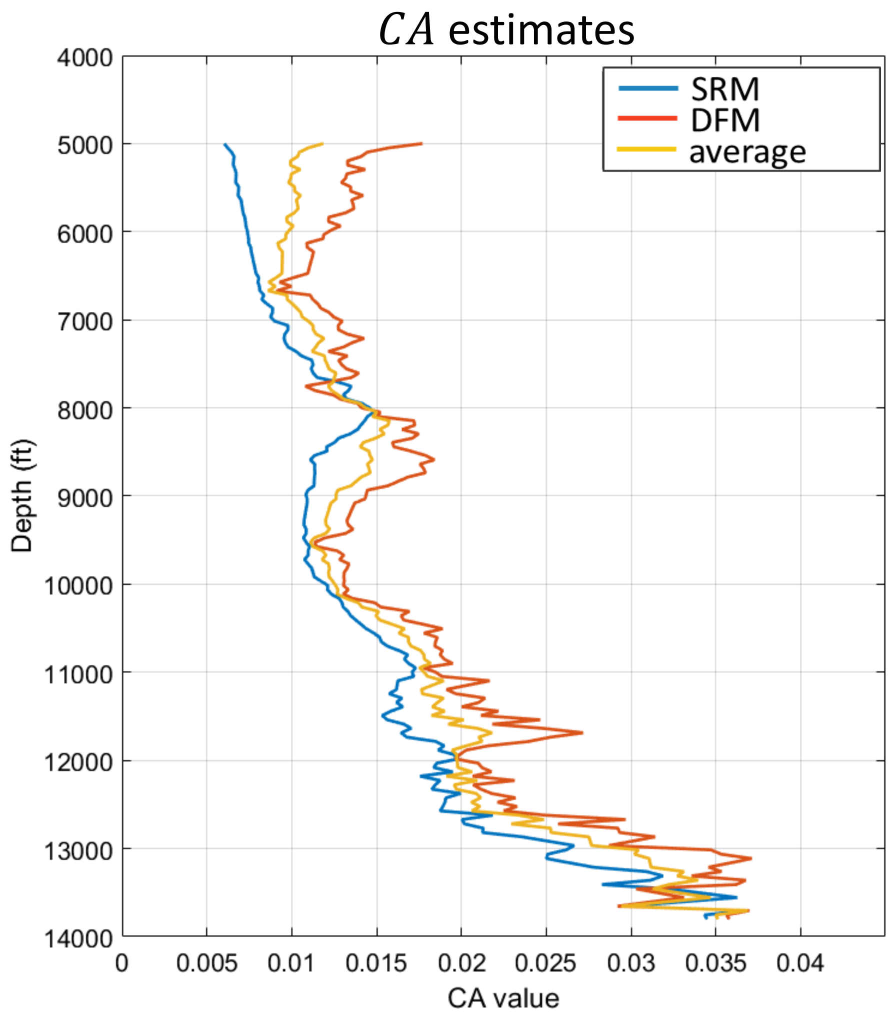
Two different CA measures



Q and CA estimates on raw data

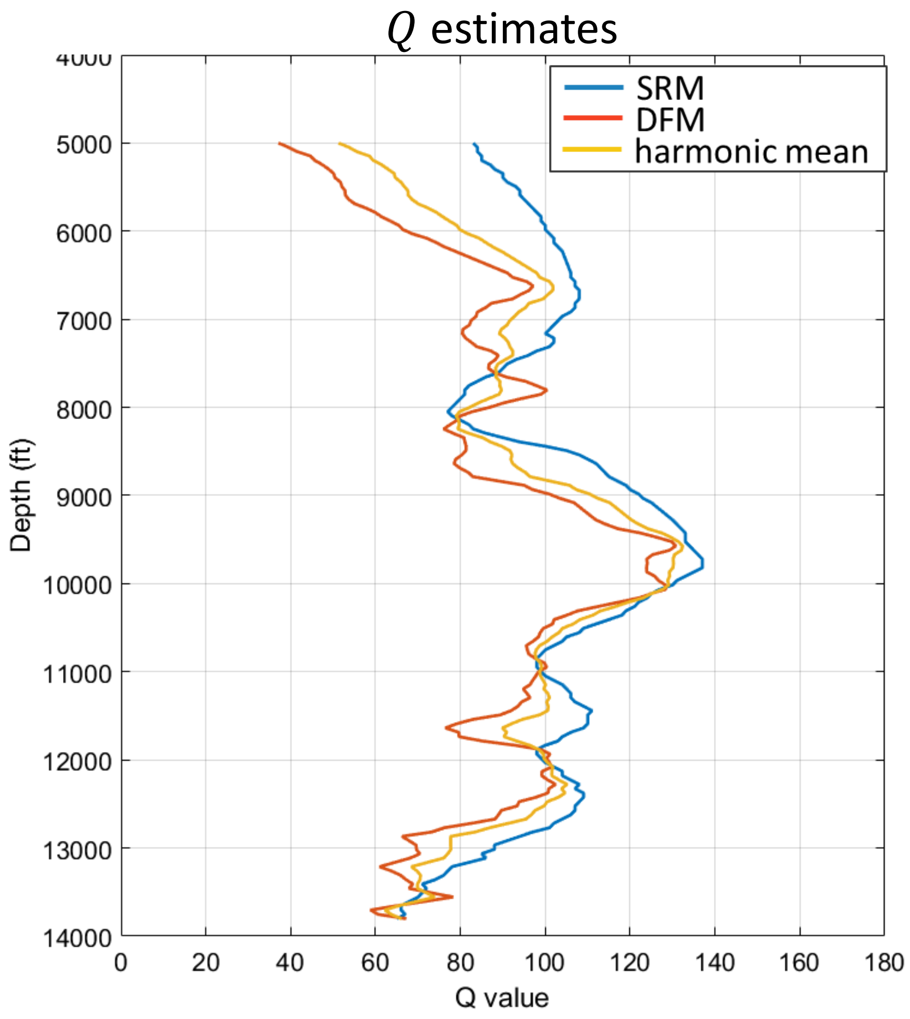
Reference level 2185 ft

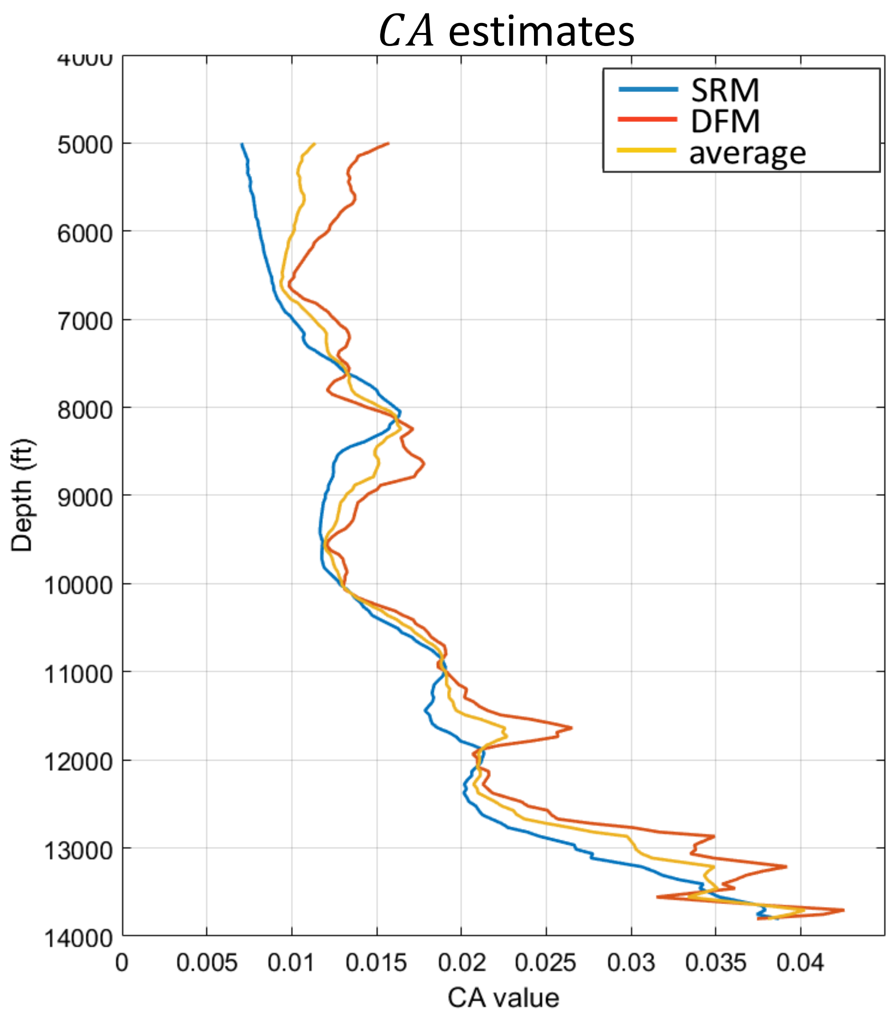




Q and CA estimates on spatially averaged data delz=100

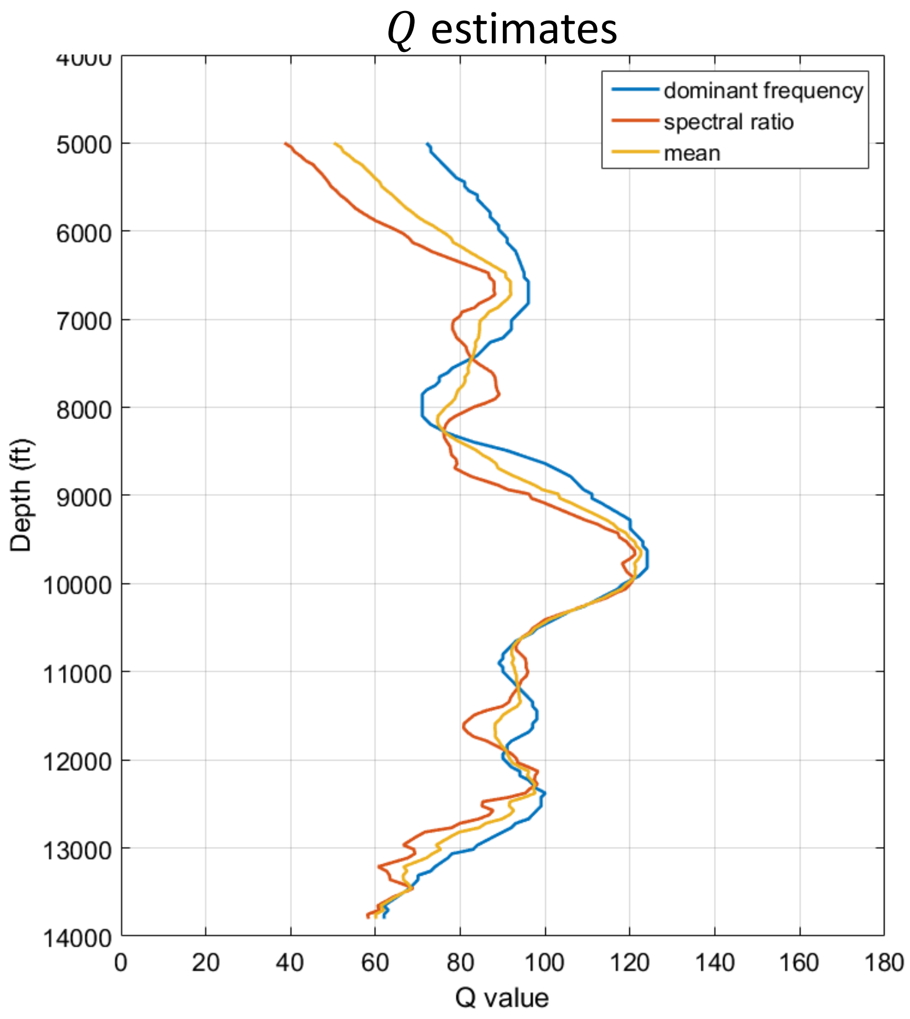
Reference level 2185 ft

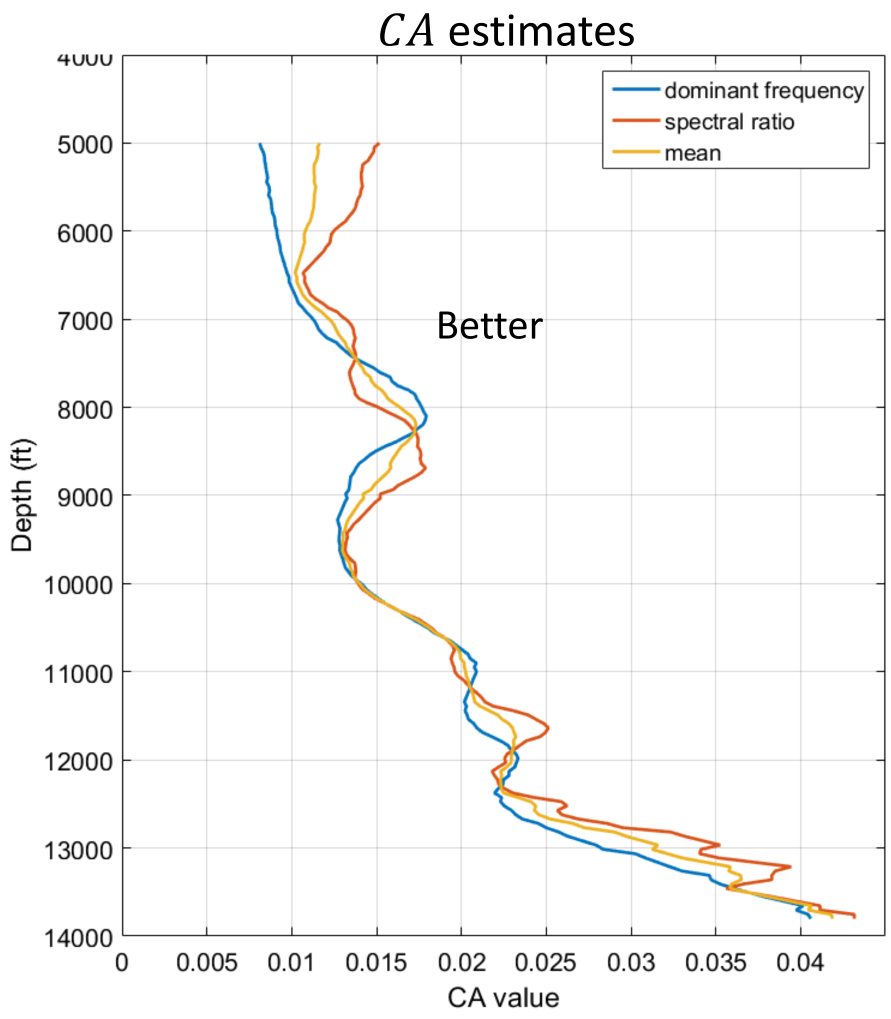




Q and CA estimates on spatially averaged data delz=200

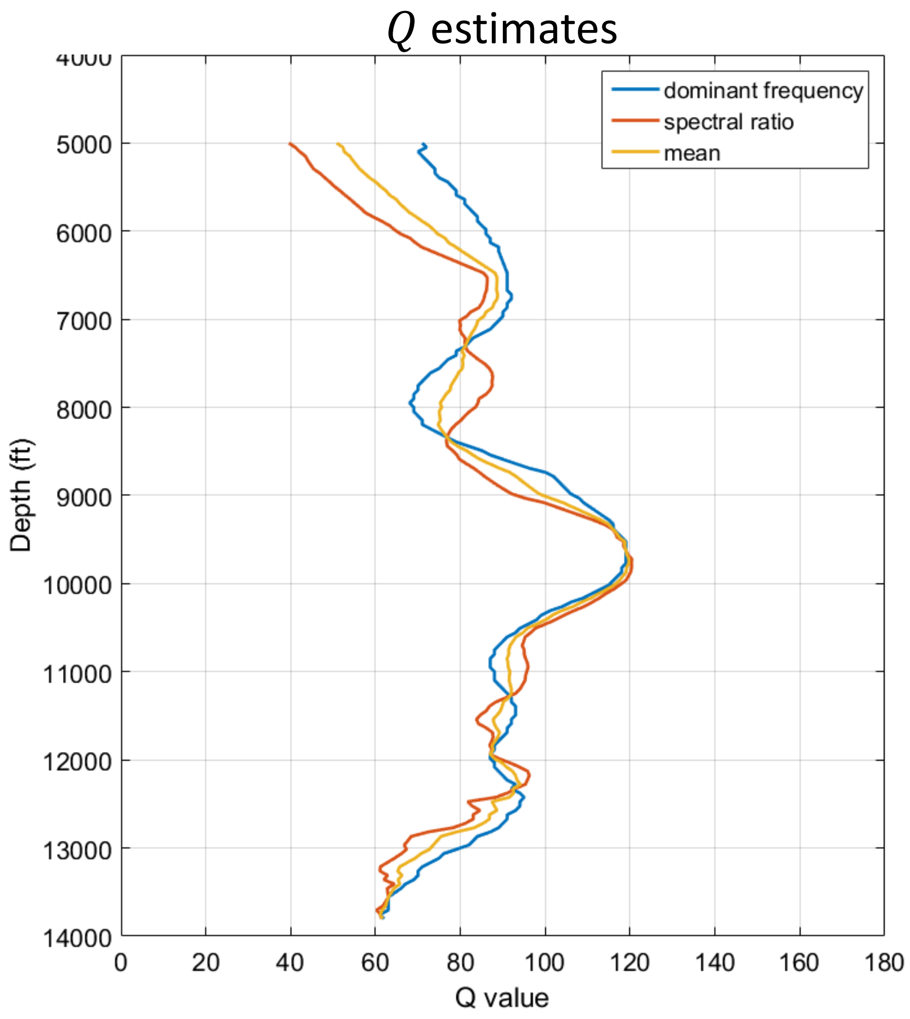
Reference level 2185 ft

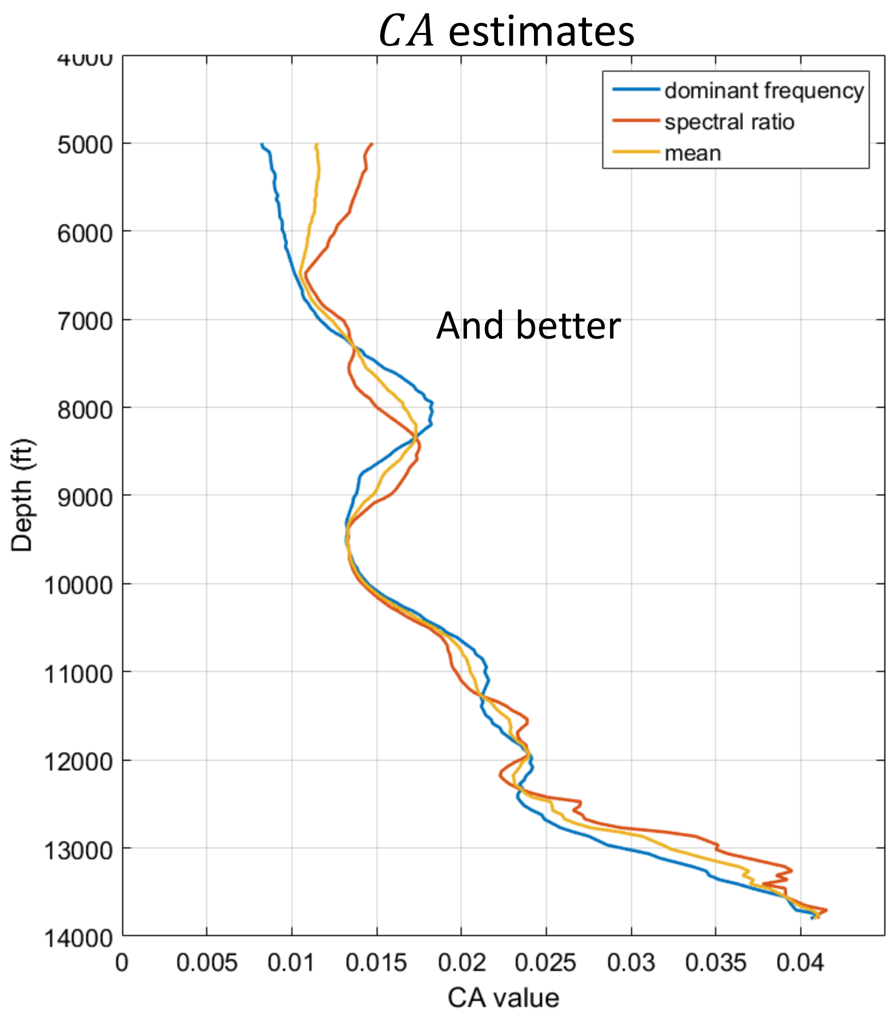




Q and CA estimates on spatially averaged data delz=300

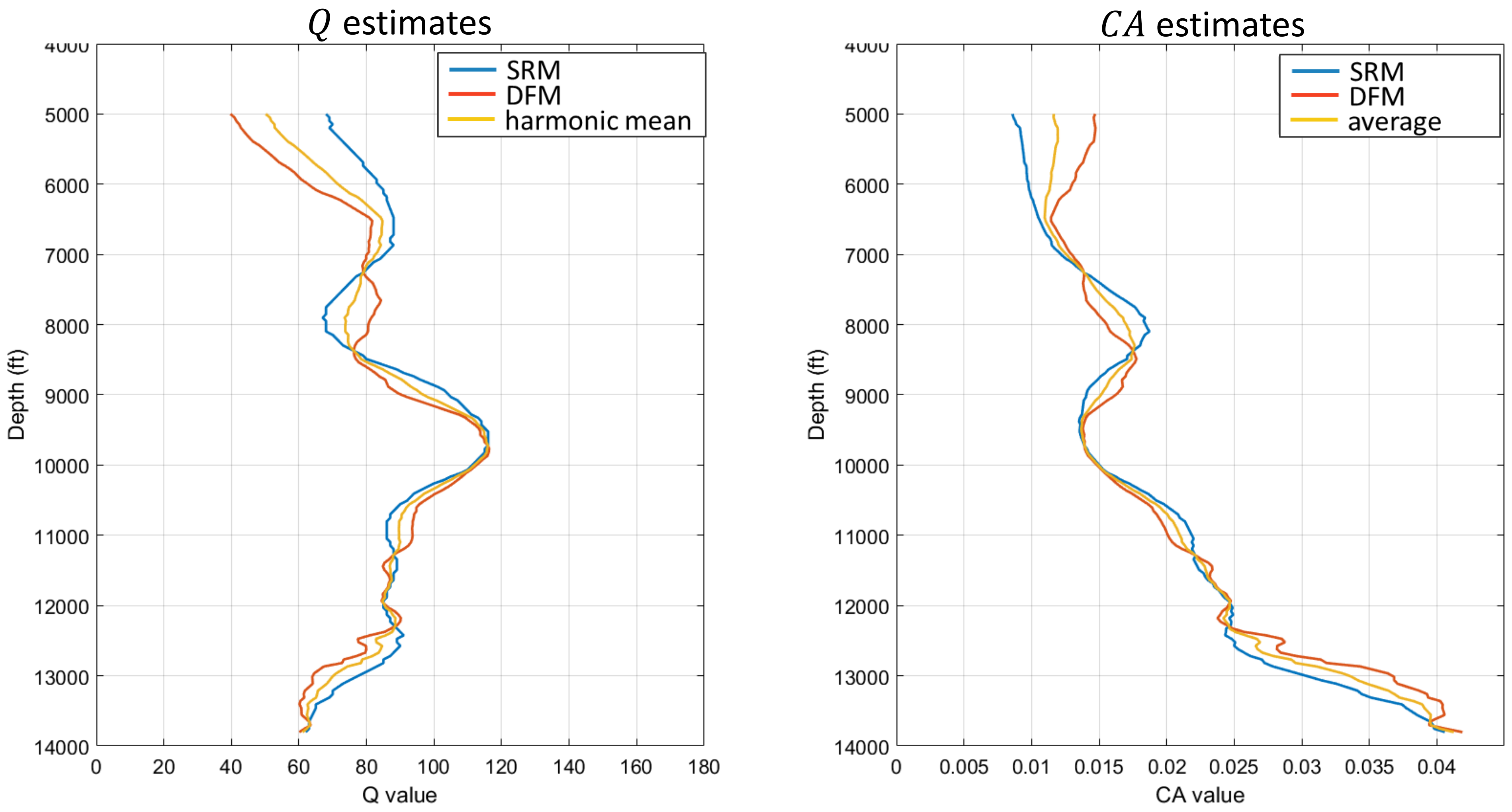
Reference level 2185 ft





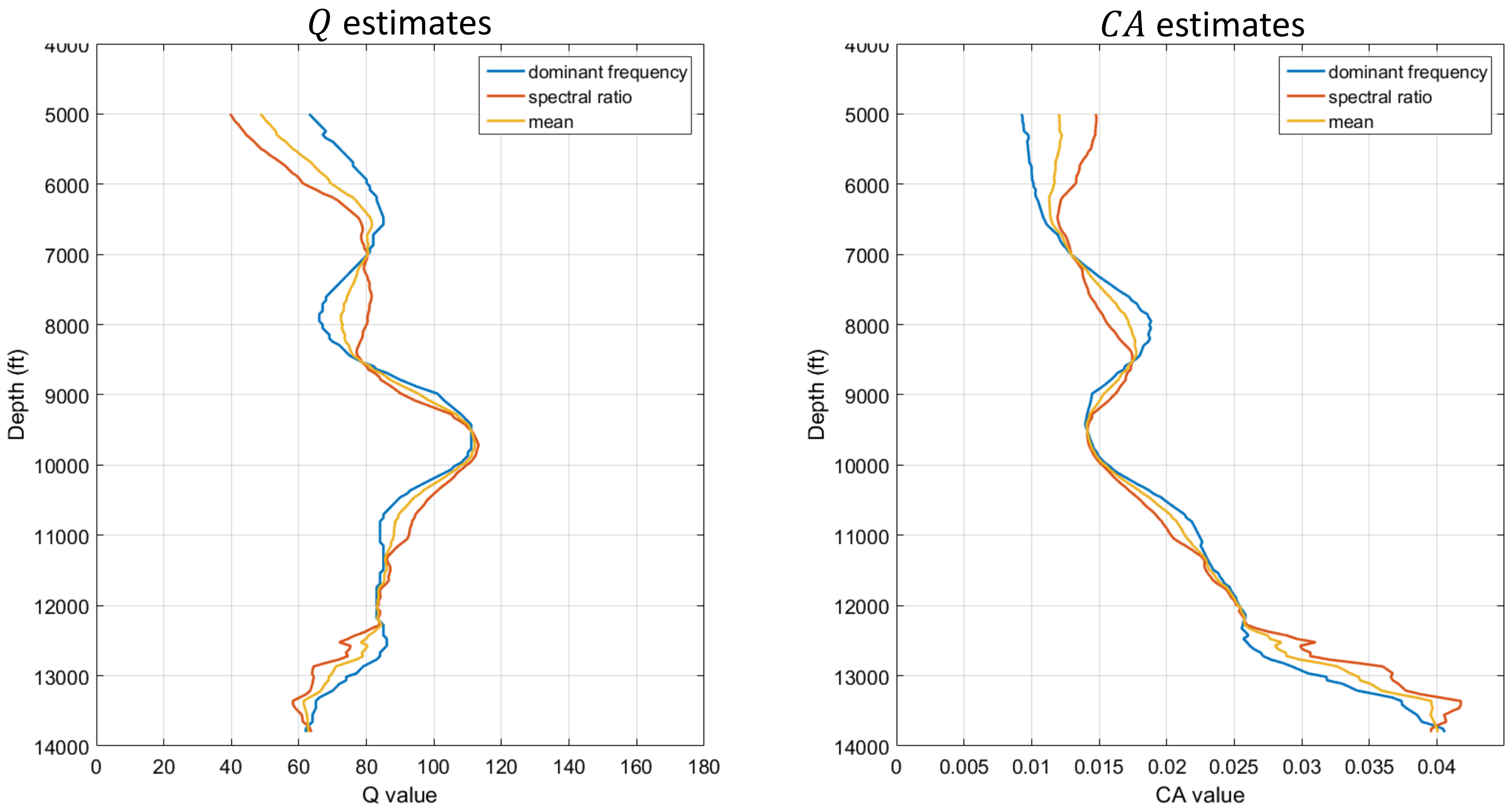
Q and CA estimates on spatially averaged data delz=400

Reference level 2185 ft



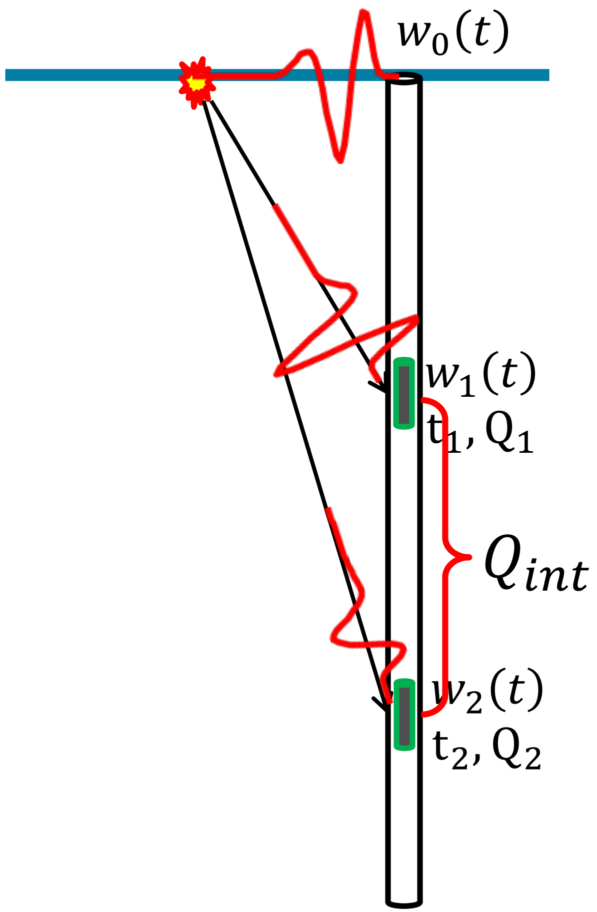
Q and CA estimates on spatially averaged data delz=500

Reference level 2185 ft



Extending the estimates to the surface

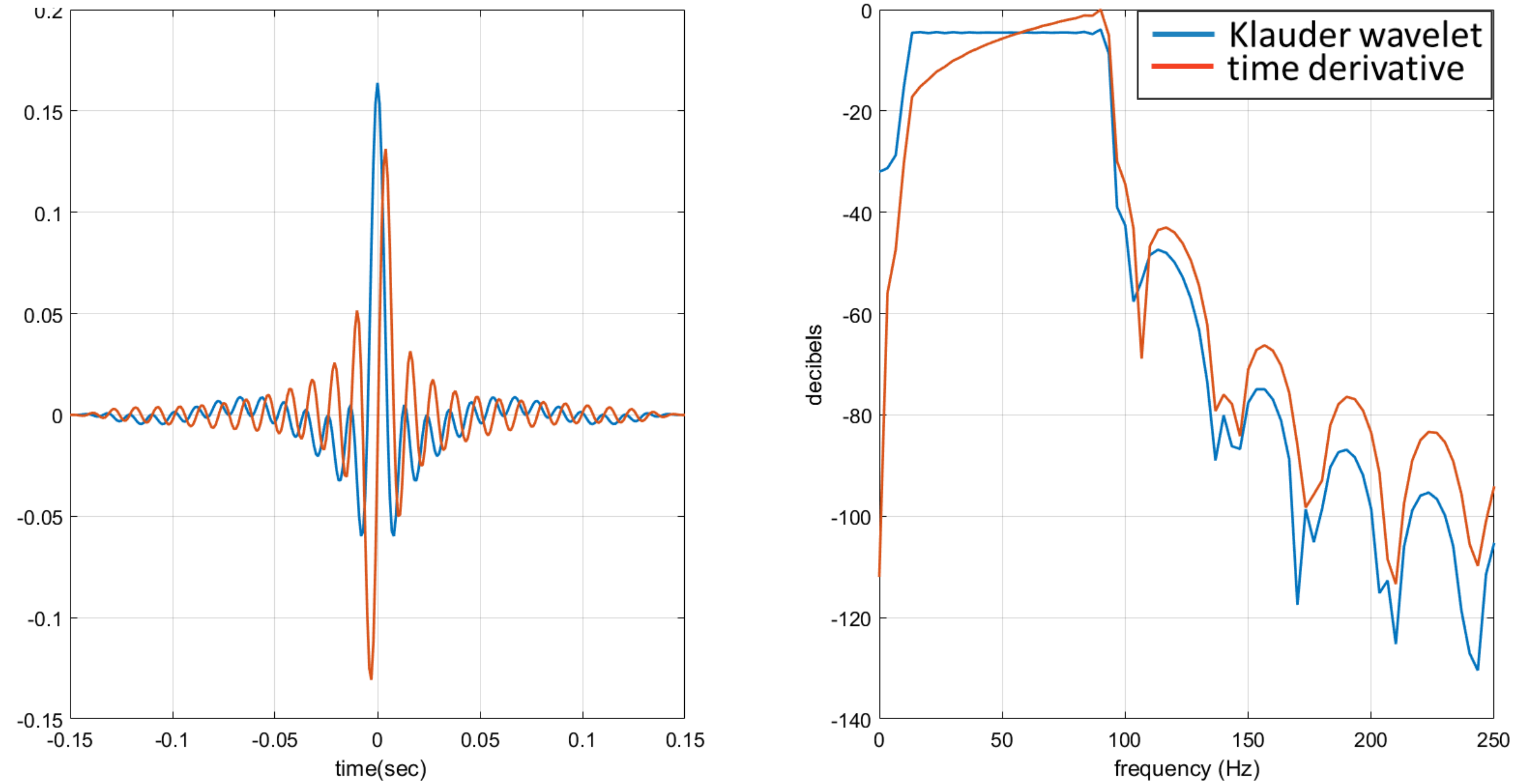
Going from reference level 2185 ft. to reference level 0 ft.



- Attenuation measurements require the comparison of two signals.
- Measurements thus far compare the "shallowest" receiver to deeper receivers. Therefore all attenuation measures are relative to the depth of the shallowest receiver.
- Extending measurements to $z = 0$ requires knowledge of the signal at that depth.
- We have no receiver there, but, in theory we know the amplitude spectrum of the source wavelet.
- Two source options:
  1) Source wavelet is Klauder wavelet
  2) Source wavelet is time-derivative of Klauder wavelet

The wavelets

Klauder and its time derivative, balanced in amplitude.



Modified analysis ribbon, with Klauder wavelet in column 1

After a spatial mix. Essentially each trace is the average of neighboring traces over +/- 500m

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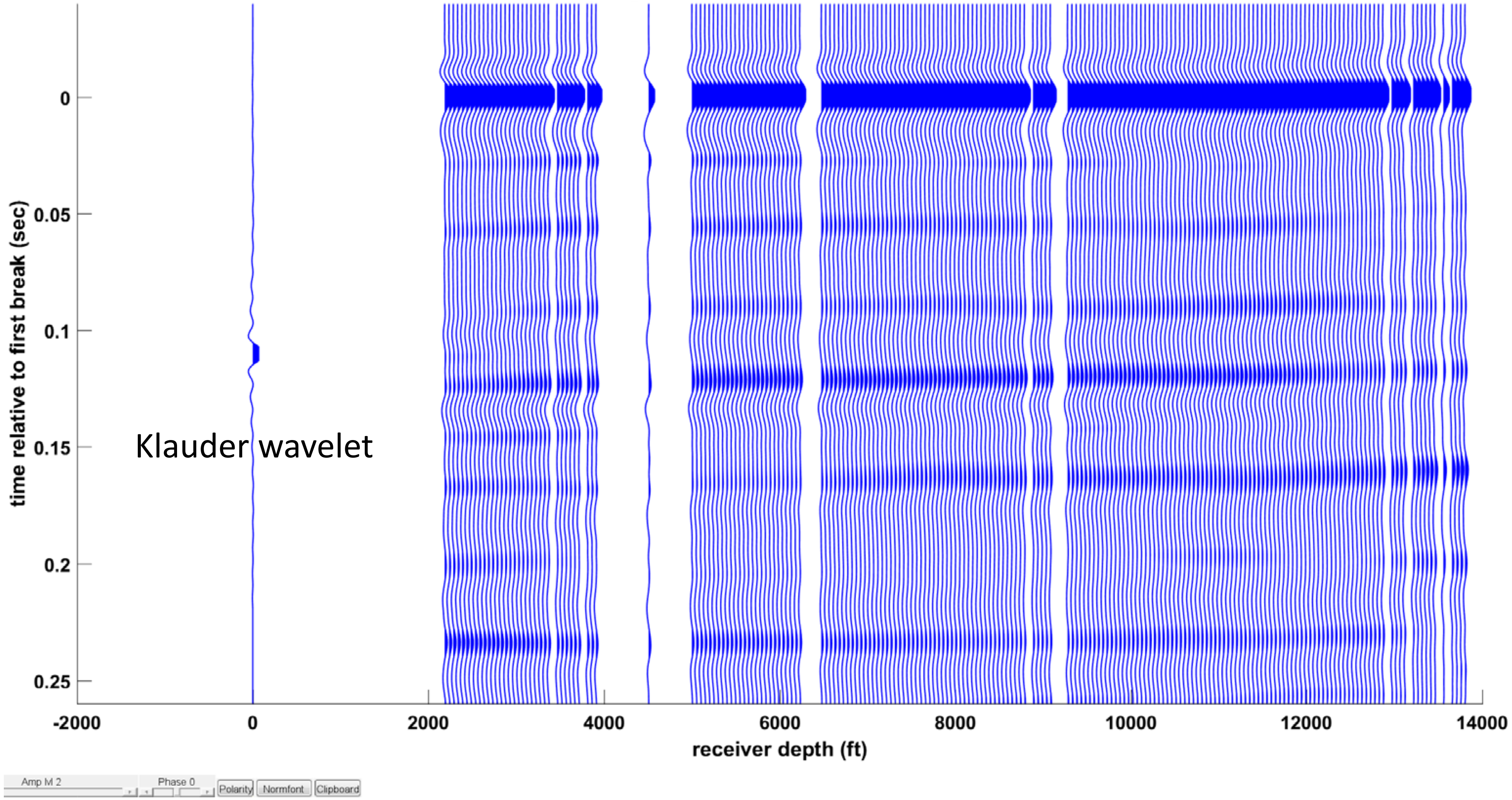
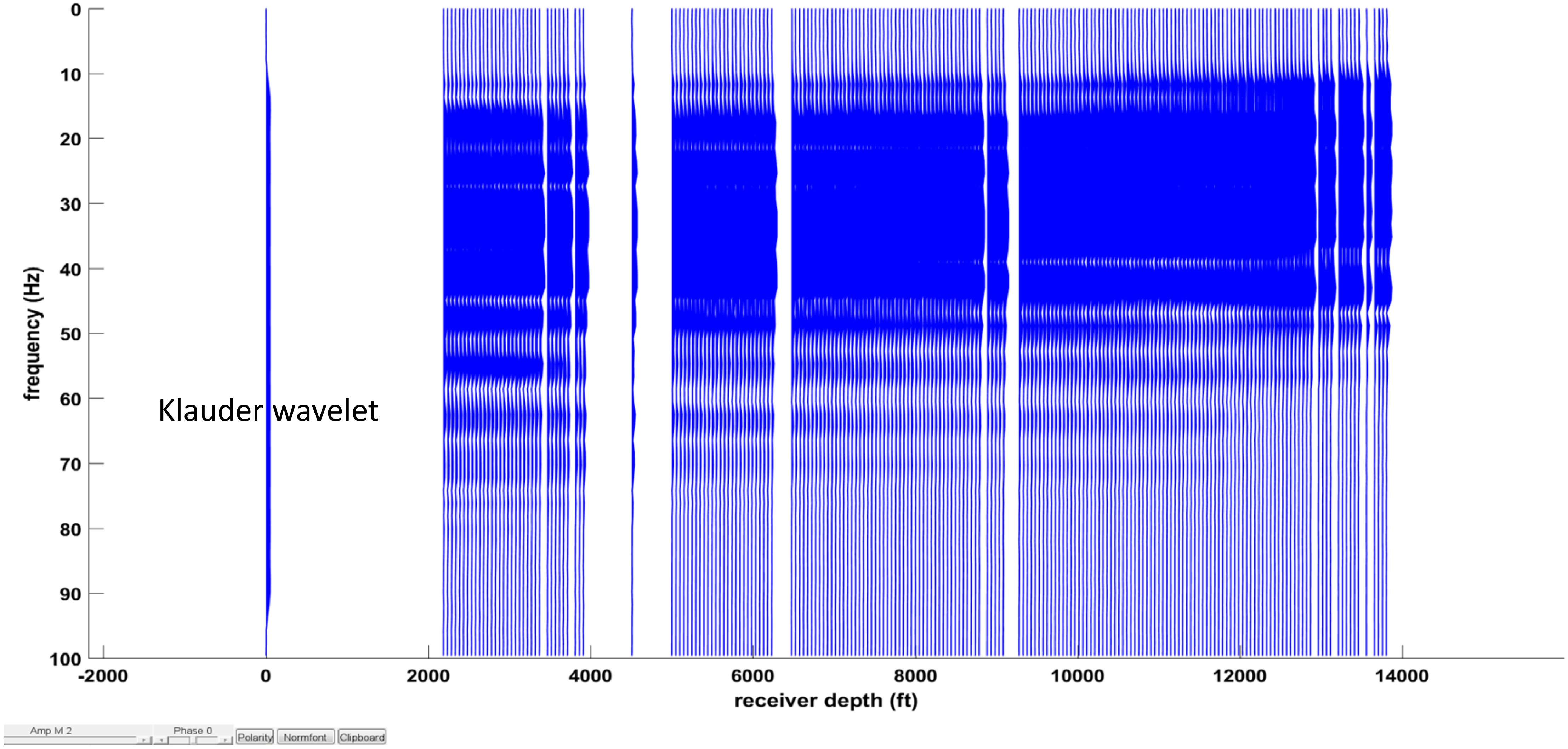
Analysis ribbon with Klauder wavelet



f-x amplitude spectrum, with Klauder wavelet in column 1

Analysis ribbon with Klauder wavelet: f-x spectra



Q and CA estimates on spatially averaged data delz=500

Reference level 0 ft, Source wavelet: Klauder 8-96Hz

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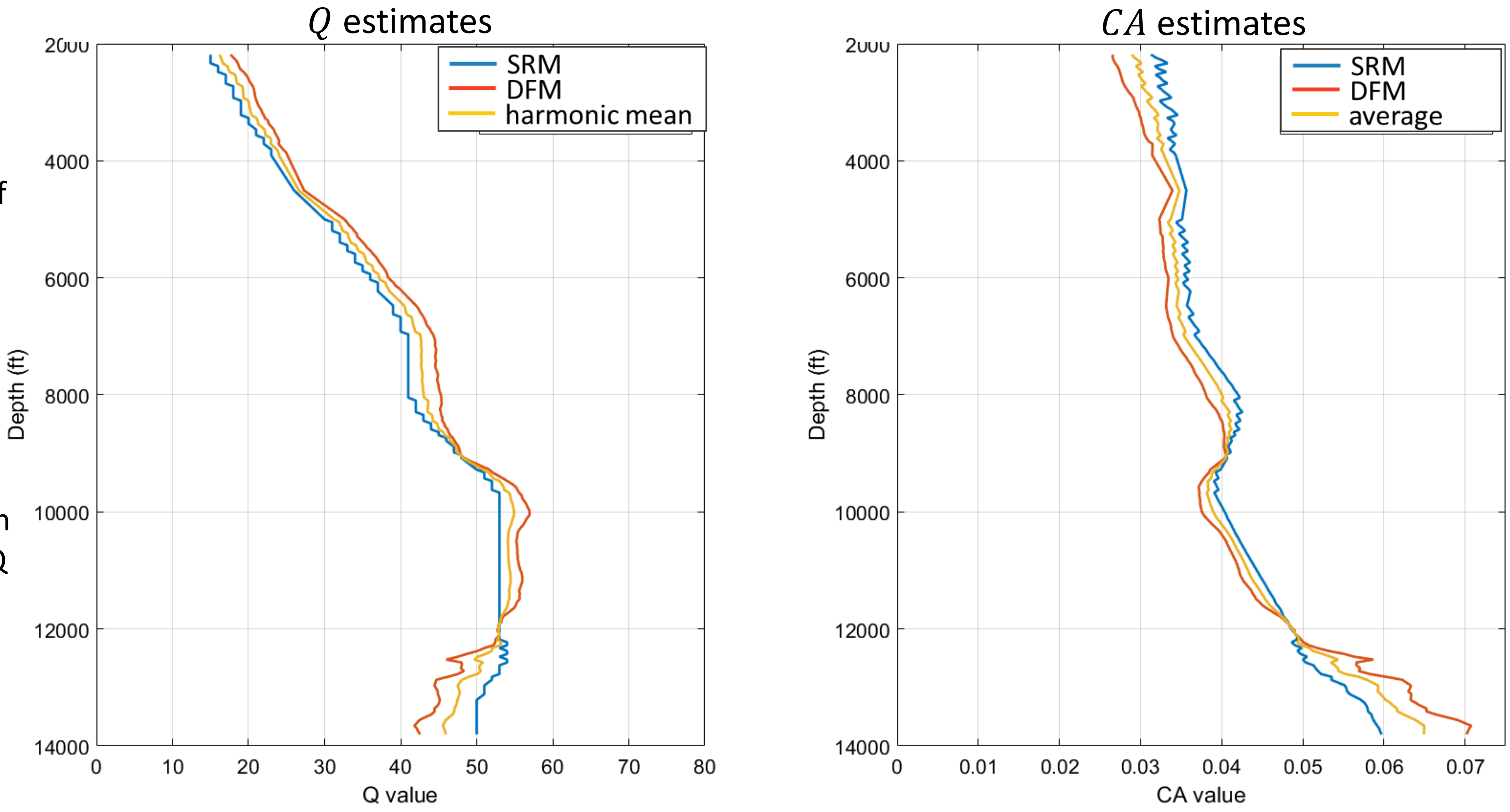
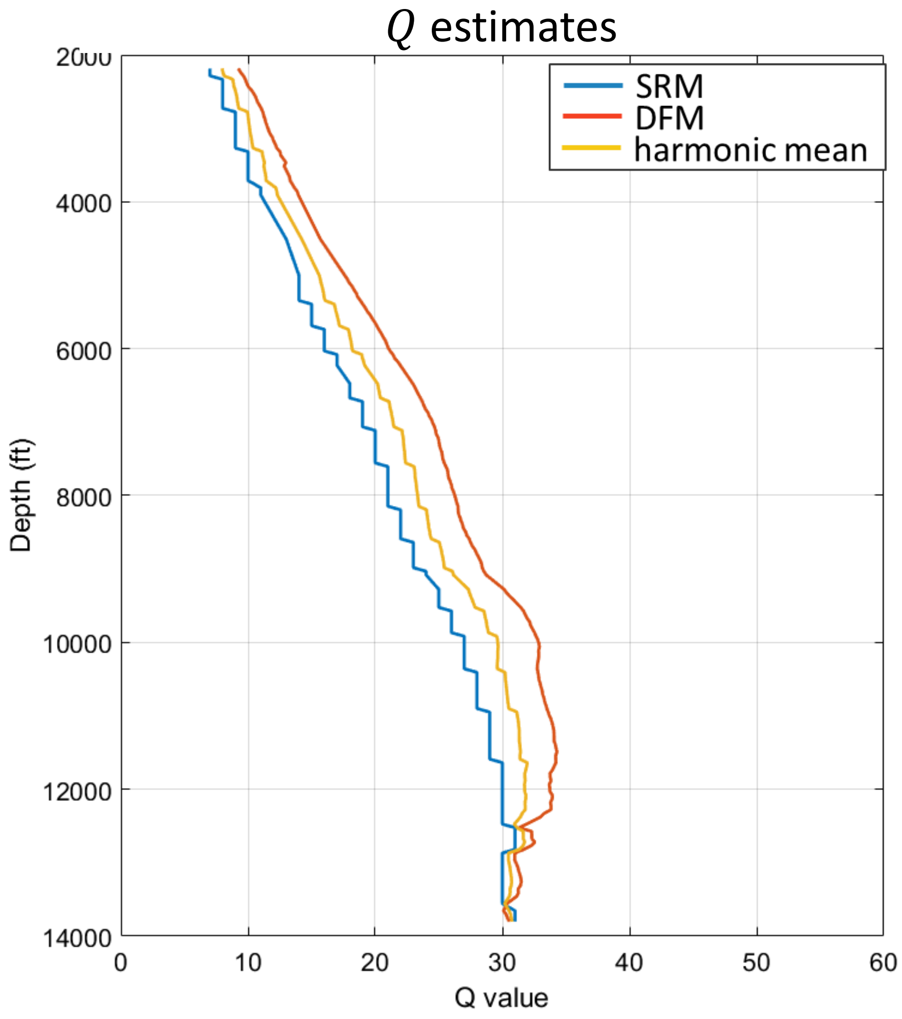
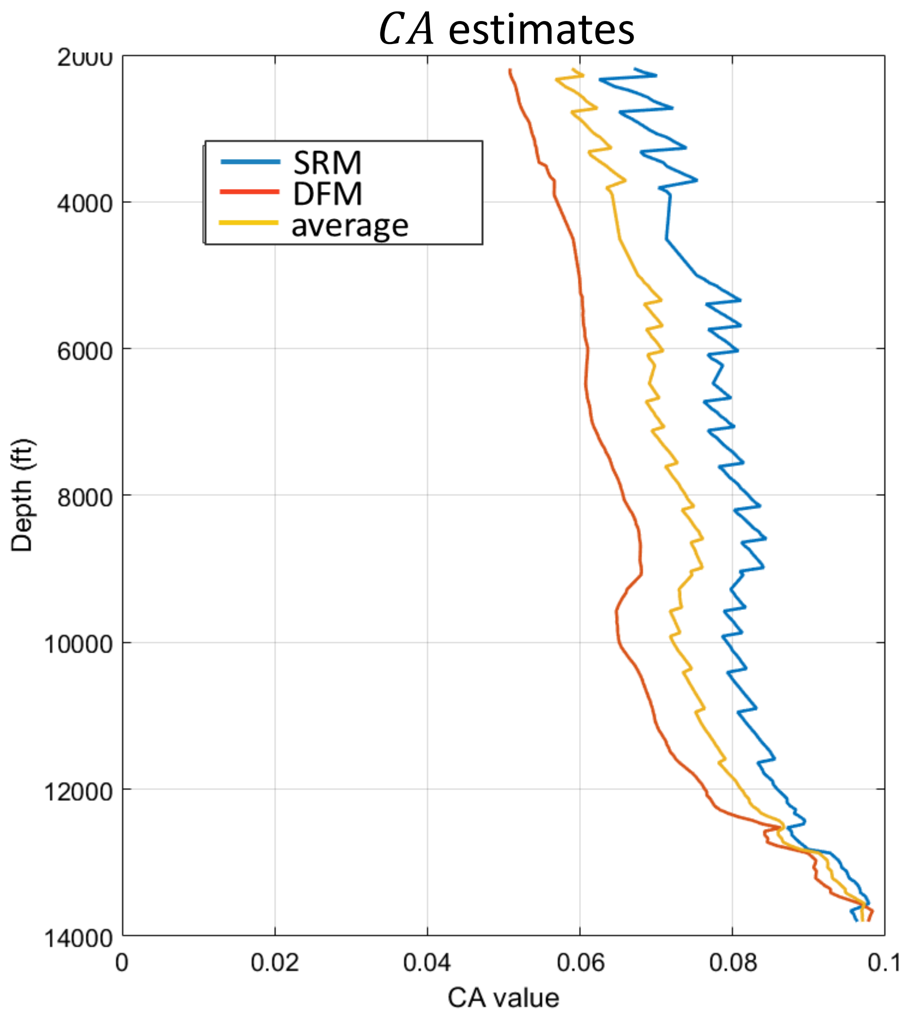
The blocky appearance of the dominant frequency result is because the objective function is minimized by a direct search over integer Q values from 5 to 250.



Q and CA estimates on spatially averaged data delz=500

Reference level 0 ft, Source wavelet: Time derivative Klauder 8-96Hz





Conclusions

- Measurement of attenuation can be considered either as Q or as CA. The latter is more stable when attenuation is low.
- Two measurement algorithms were presented:
  1) Spectral-ratio method: very sensitive to amplitude balancing and frequency range
  2) Dominant-frequency method: insensitive to amplitudes and less sensitive to frequency range.
- When applied to real VSP data, very small residual upgoing waves cause instability.
- Both methods gave similar results on spatially averaged data.
- Extension to the surface assuming a known source was investigated.
- Overall average Q values seem quite low when referenced to the surface.

  - Relative to 2185 ft, Q ranged from 60 to 110.

  - Relative to 0 ft, Q ranged from less than 20 to 55.
- This study was conducted with software in the CREWES Matlab toolbox.

Acknowledgements

I think the sponsors of CREWES, especially Devon Canada, for their support.

Devon USA made the VSP data available.

Colleagues at Devon provided valuable commentary and insight.

Spectral-ratio analysis plots