Stratigraphic filtering and Q estimation

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Outline

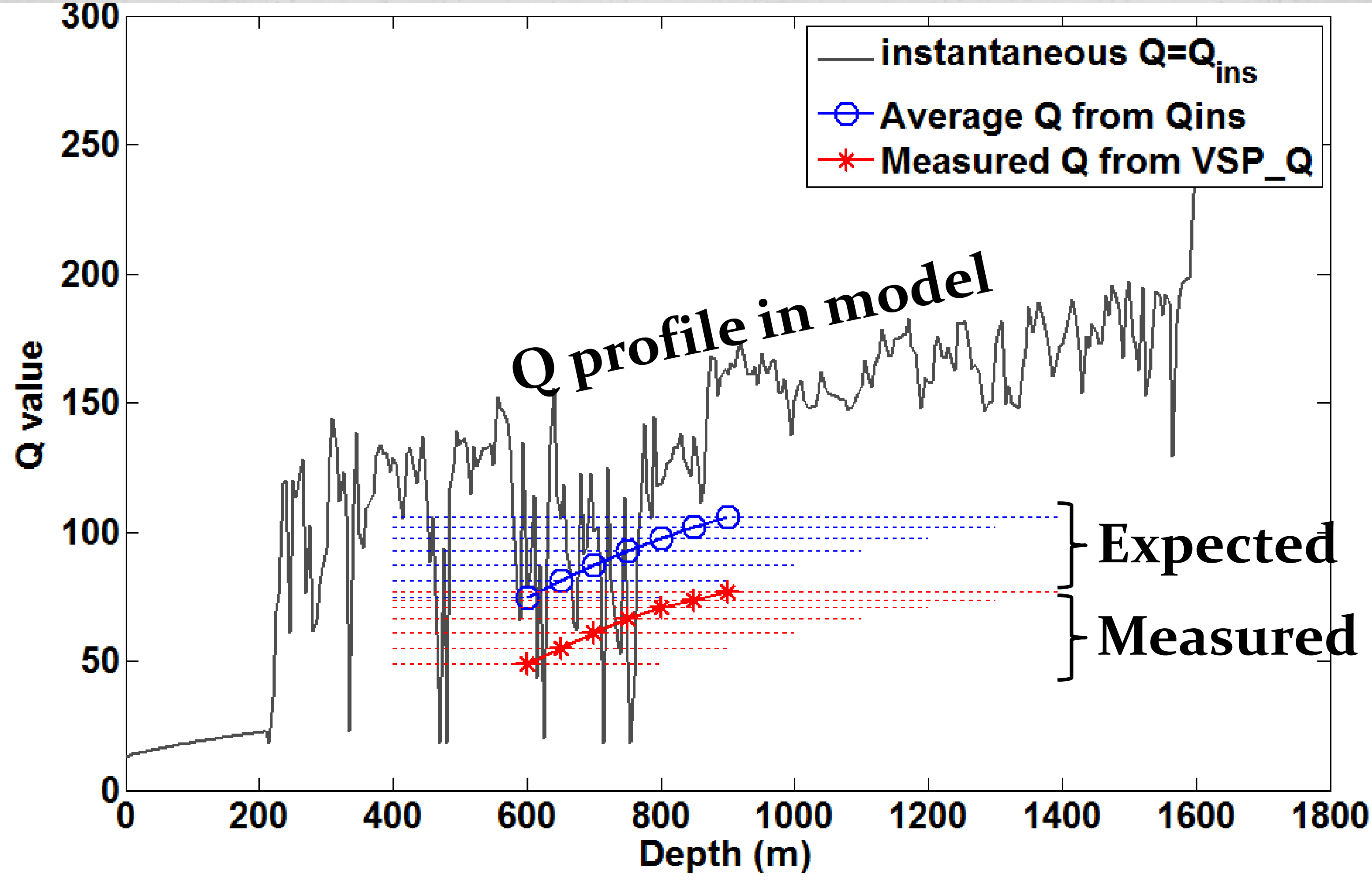
- Motivation: Are Q measurements inherently biased?
- The measurement of Q*
- Synthetic VSP with attenuation*
- A synthetic VSP from well logs
- Searching for the cause of the bias
- Stratigraphic filtering (O’Doherty and Anstey)
- Direct measurement of Q_{strat}
- Conclusions

* Indicates new or updated CREWES software released this year.

Motivation

Q estimated by spectral ratio from synthetic VSP

A systematic error?



Possible Causes

- The Q estimation code is wrong (buggy)
- The synthetic VSP code is wrong (buggy)
- Transmission effects are biasing the Q estimate
- Surface-related multiples are biasing the Q estimate
- **Internal multiples are biasing the Q estimate**
- Something else entirely…

Measurement of Q

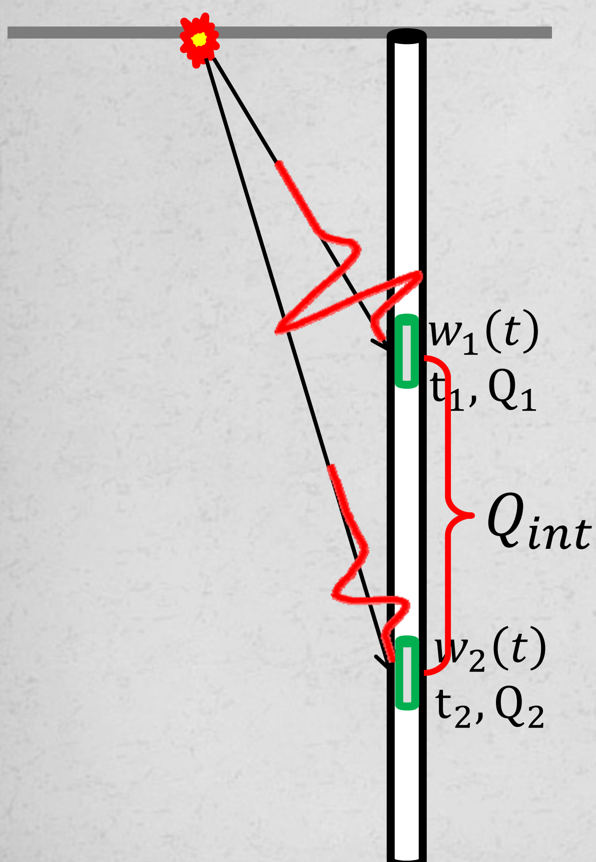
CREWES tools:

1) ***Spectral Ratio***

2) Spectral Matching

3) Dominant frequency matching

Spectral Model



Form the log-spectral-ratio

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

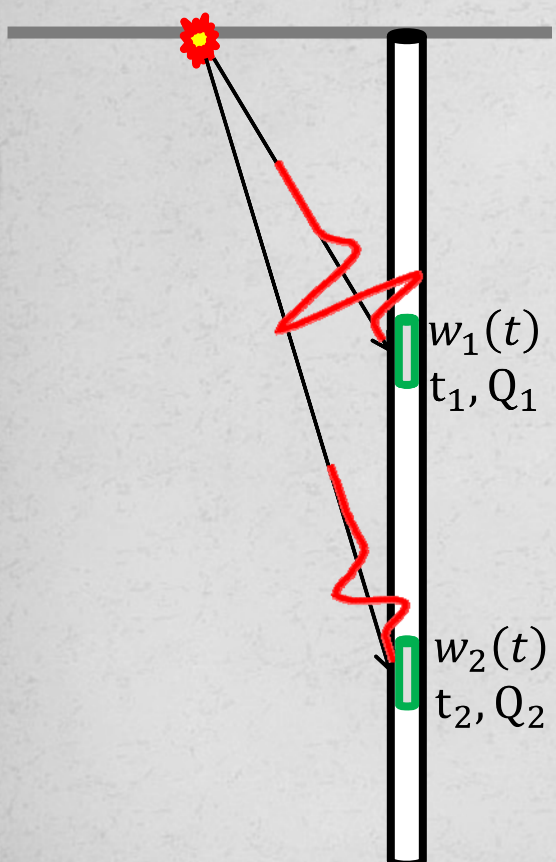
T = transmission coefficient

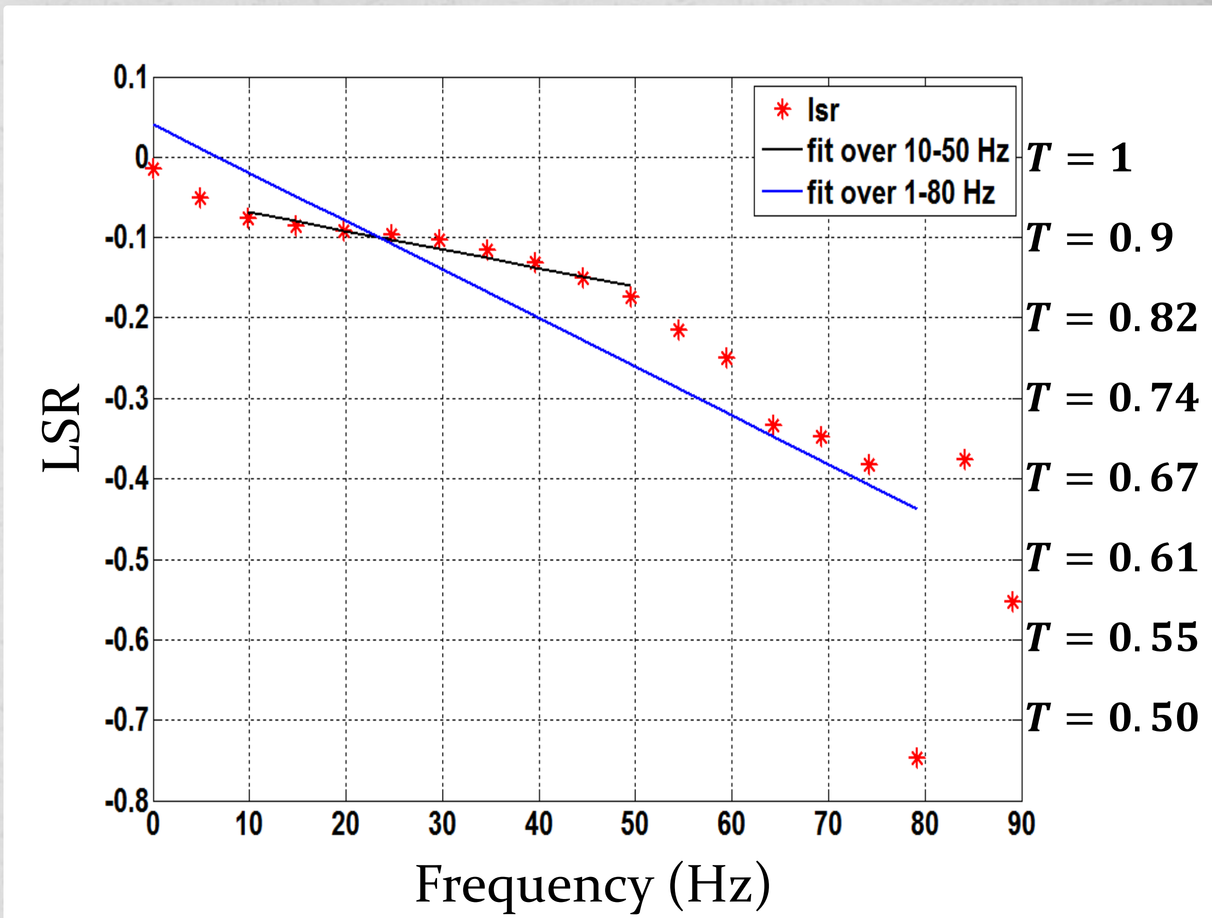
A_1, A_2 = amplitude spectra

Strategy:

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

Log Spectral Ratio

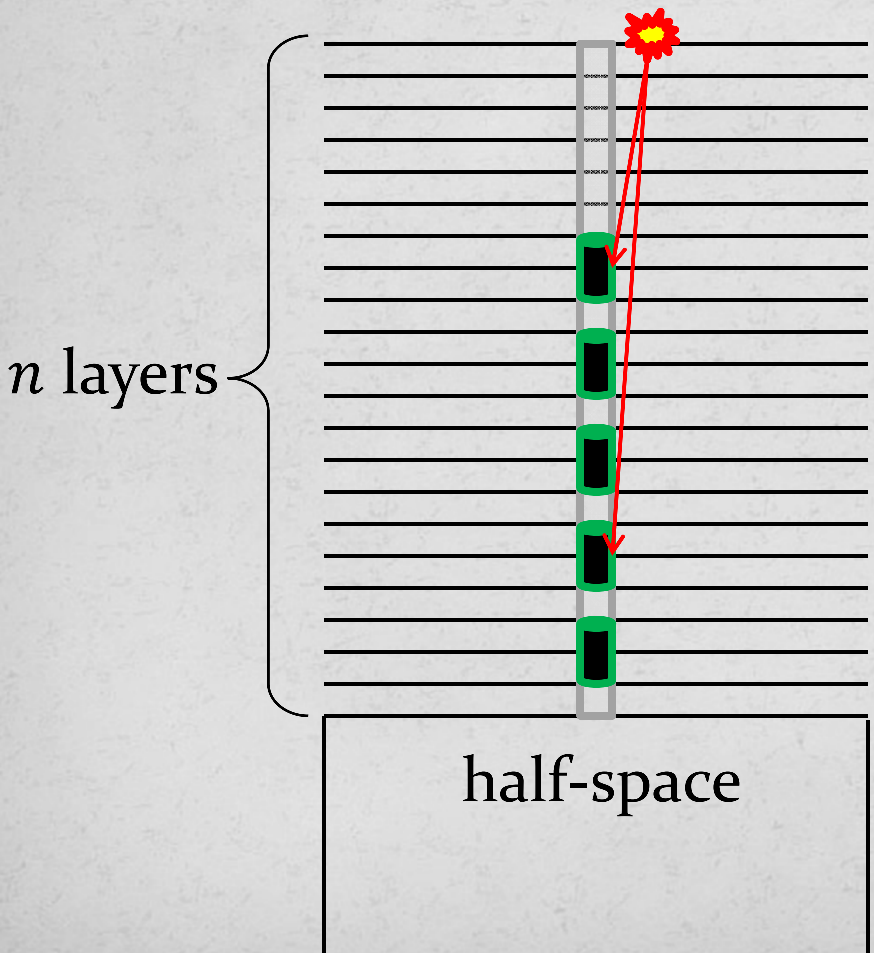




Predicted values for Q and T depend on the frequency range of the fit.

Synthetic VSP with Attenuation

Construction of a Synthetic VSP after Ganley (1981, Geophysics)



- 1D layered earth
- source at z=0
- receivers at arbitrary depths
- Includes effects of
    - transmission
    - reflection
    - multiples
    - Q

VSP construction

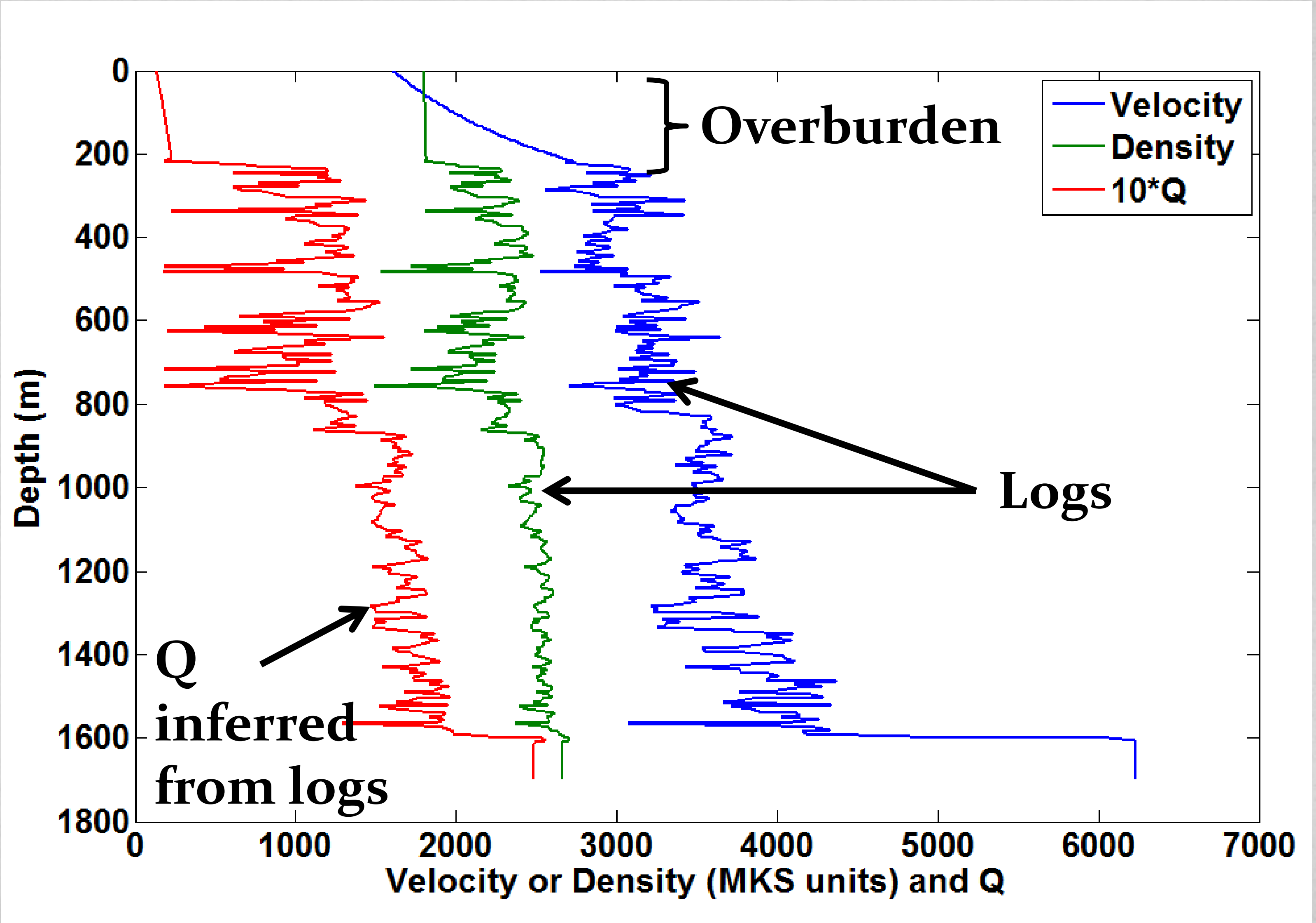
Algorithm features

1. Code uses frequency-domain layer matrices not finite differences.
2. The model $v_p, \rho,$ and Q can be specified with great detail.
3. Frequency dependence of traveltimes and reflectivity are honored.
4. All possible multiples can be calculated.
5. Multiples, transmission loss, and attenuation can be individually turned off with a simple modification of the layer matrix.
6. All effects are included with great accuracy.

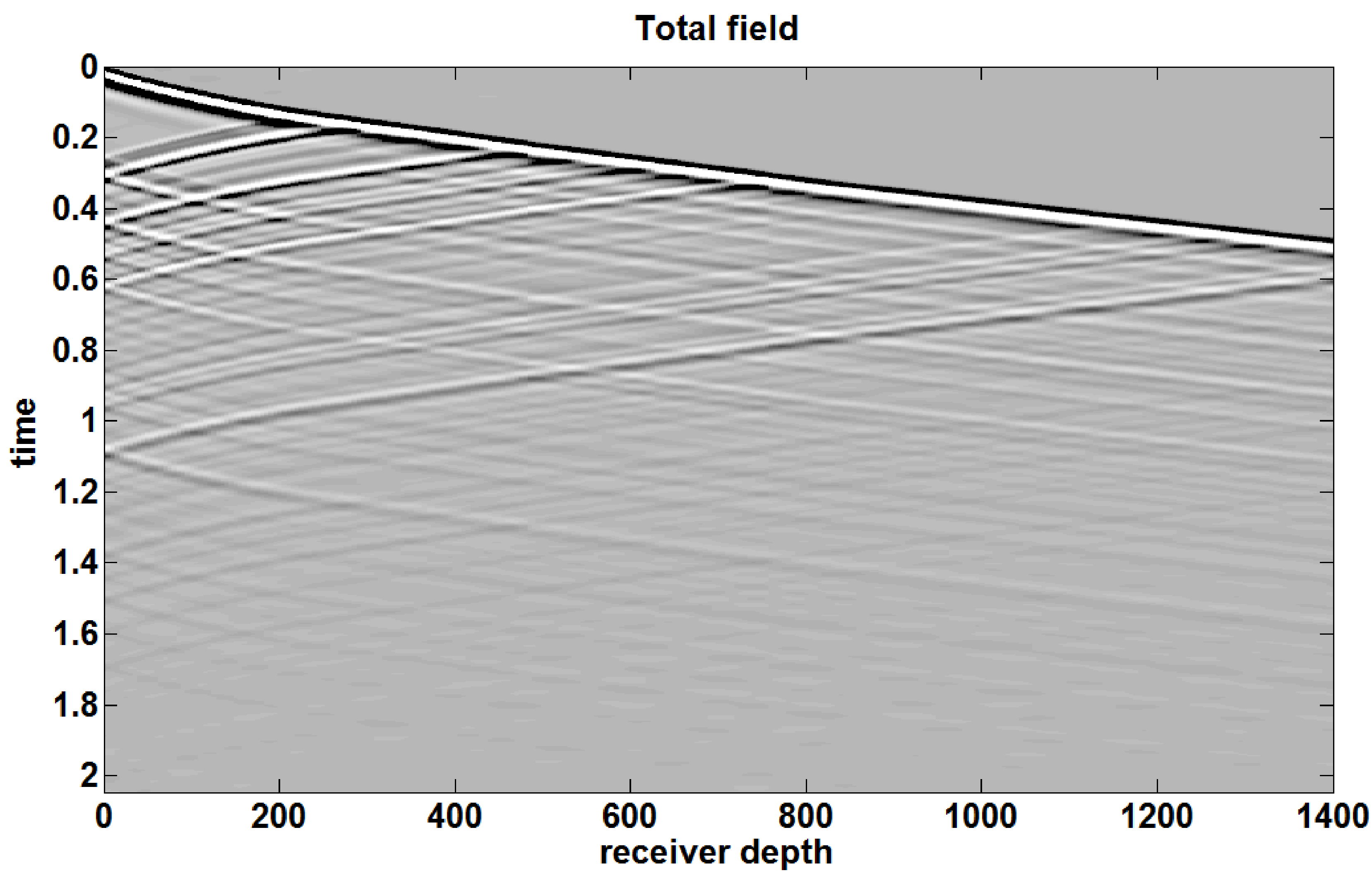
More details can be found in the research report or at my poster this afternoon.

Synthetic VSP from well logs

Well information with Fake Q

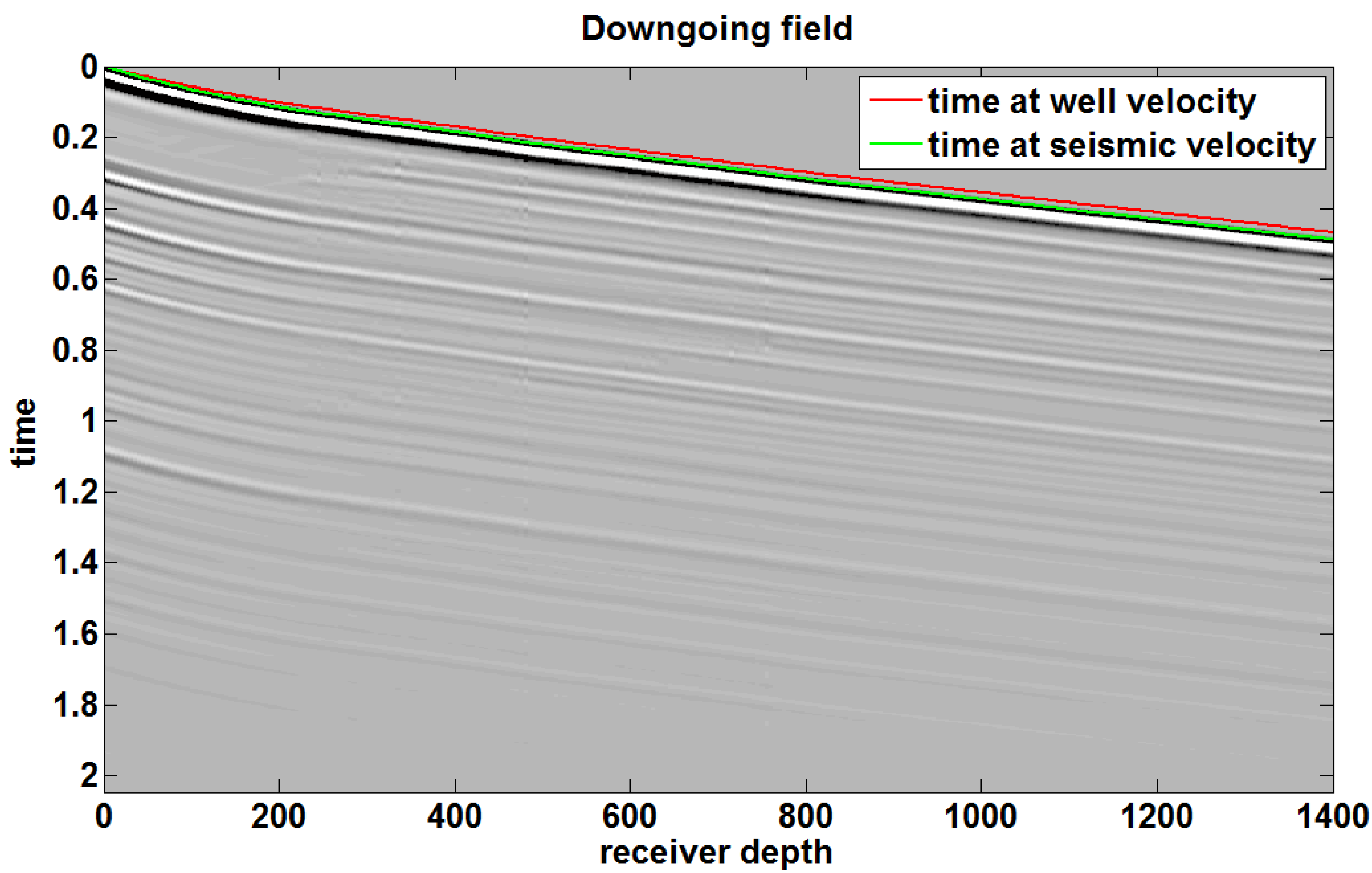


VSPMODELQ
total field



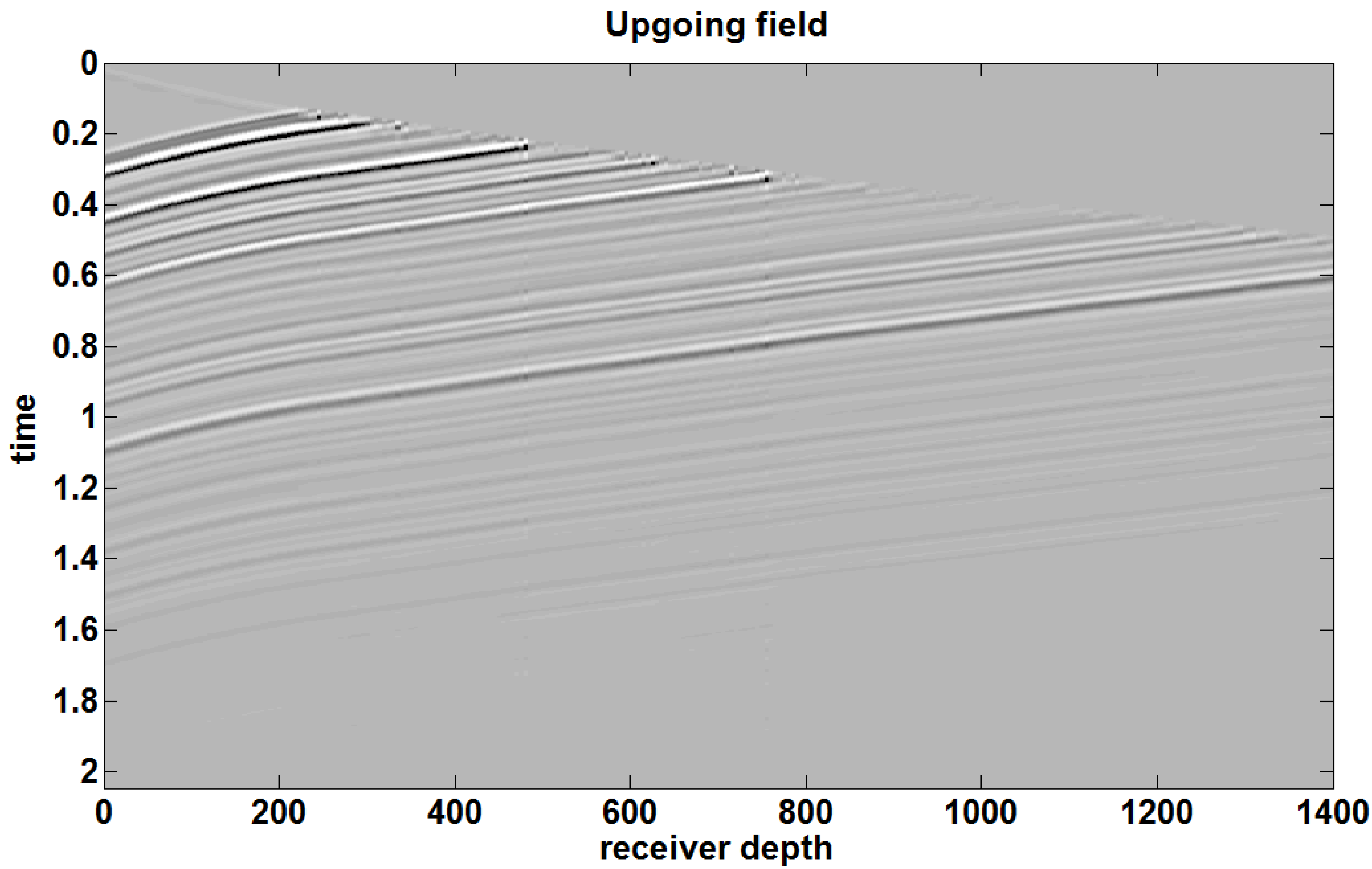
VSPMODELQ

downgoing field



VSPMODELQ

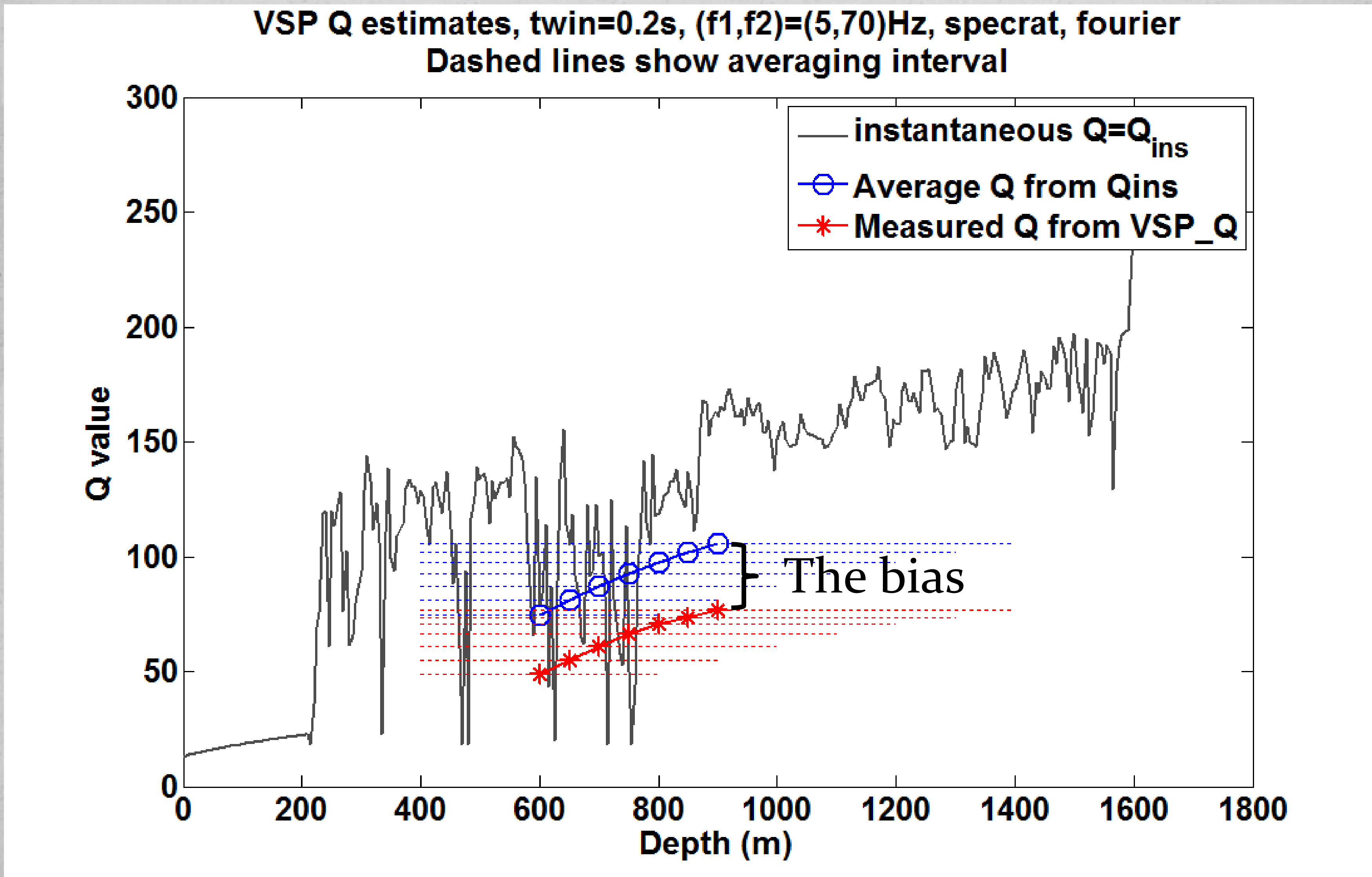
upgoing field



Searching for the cause of the bias

From the well-based model

Q estimated by spectral ratio
from total downgoing field

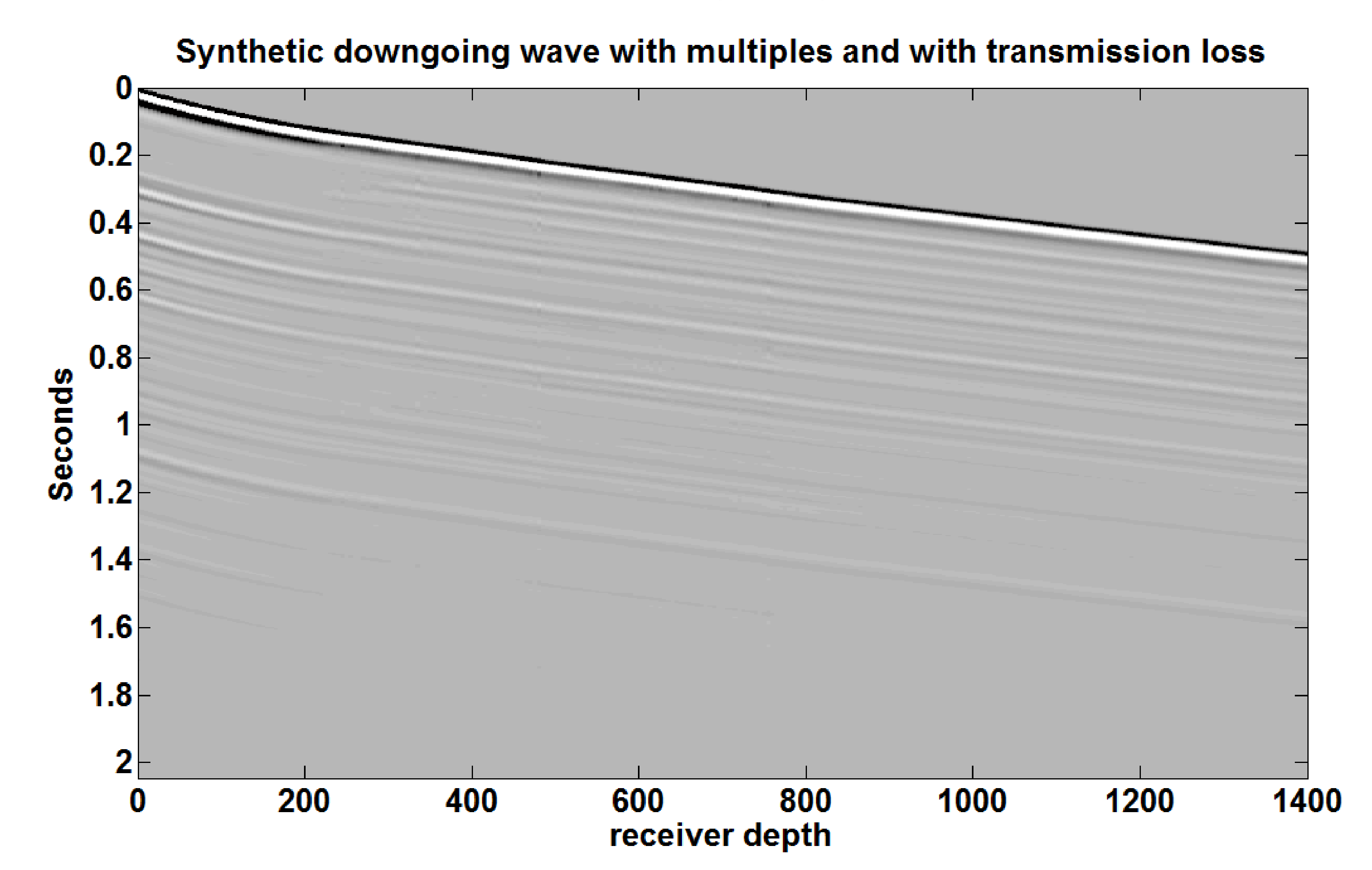


Is the Q estimation algorithm wrong?

Test by creating a pure downgoing wave with Q effects but no transmission losses or multiples. Measure Q on this wave.

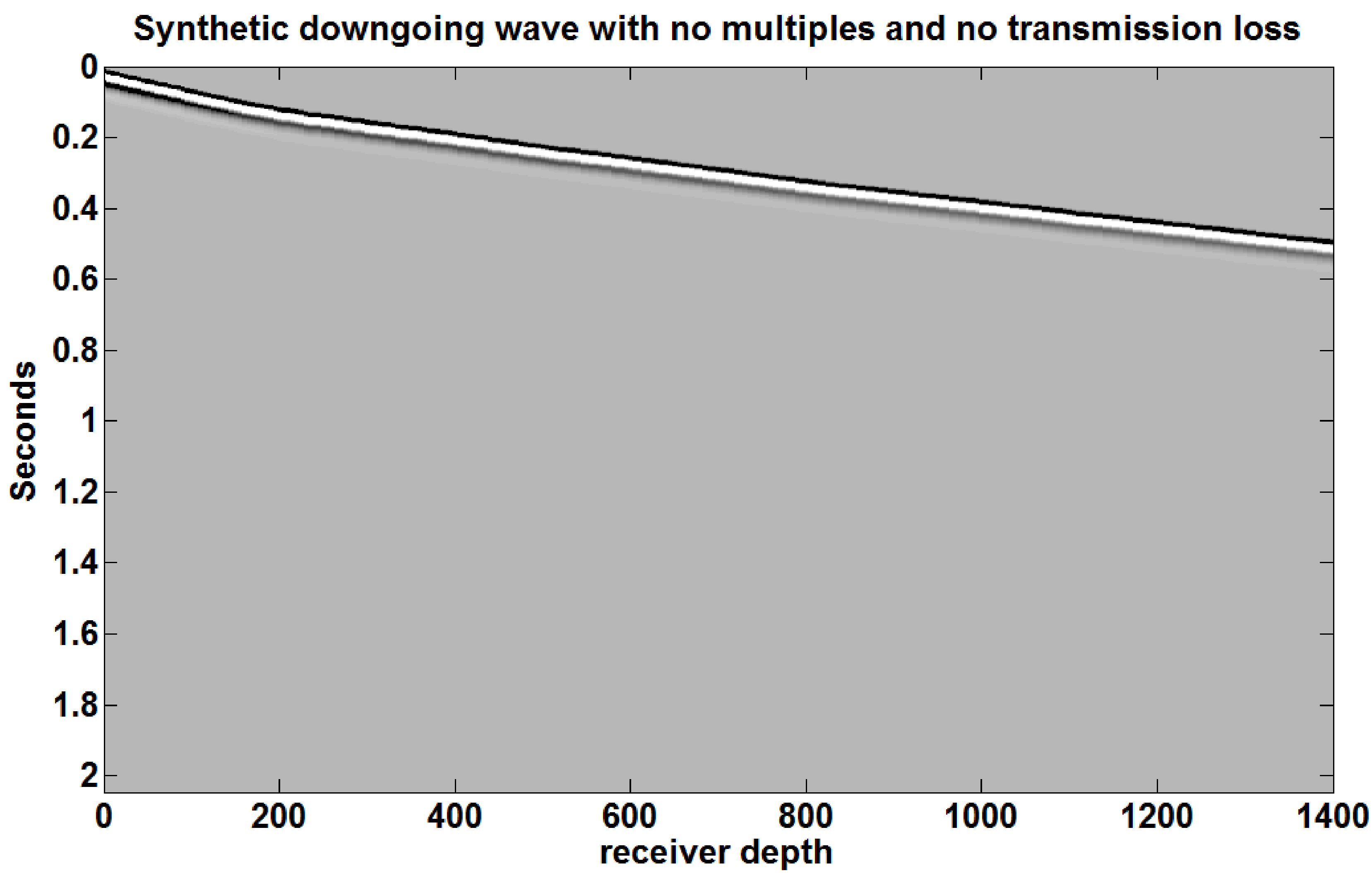
VSPMODELQ

total downgoing field

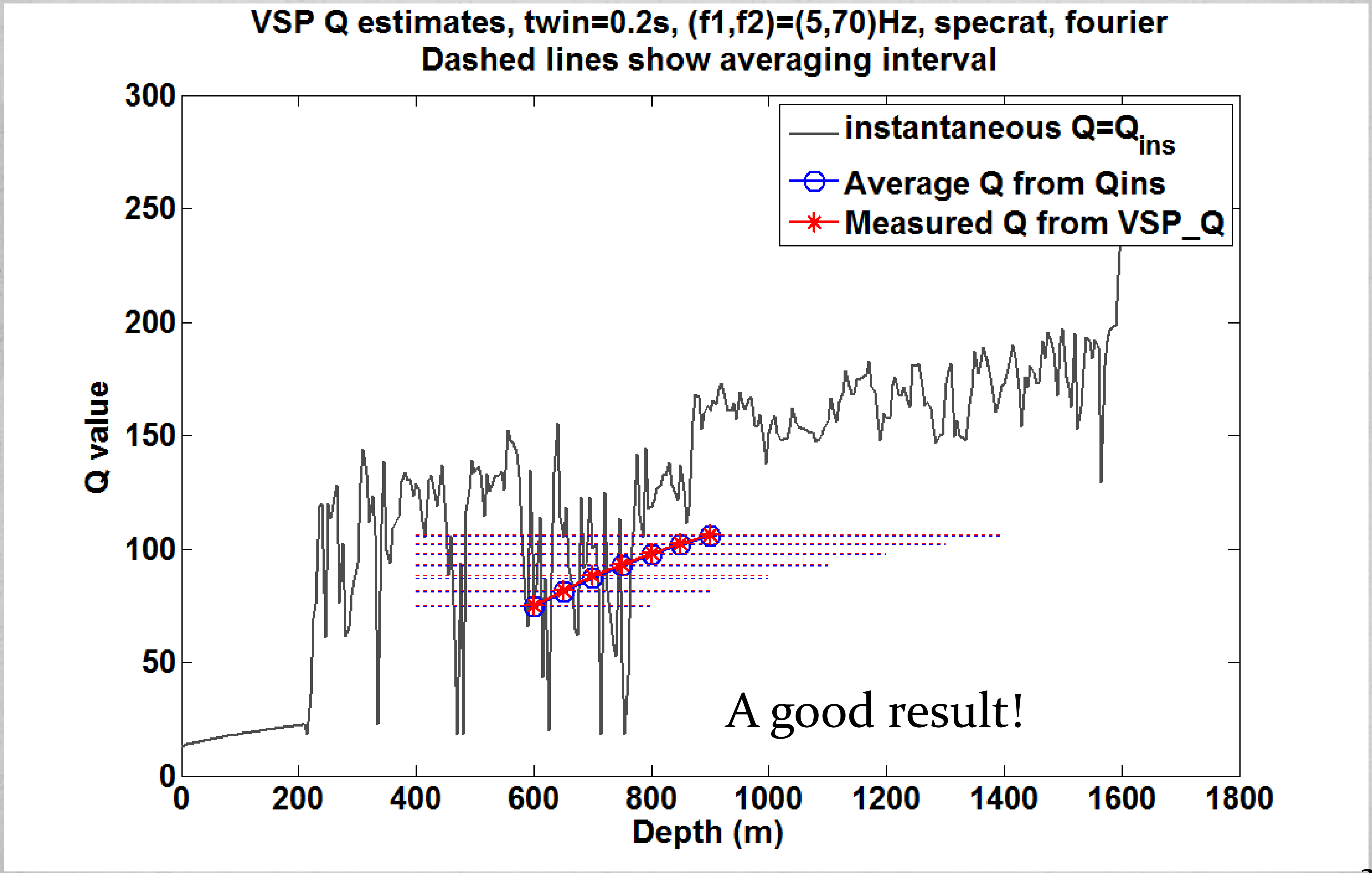


VSPMODELQ

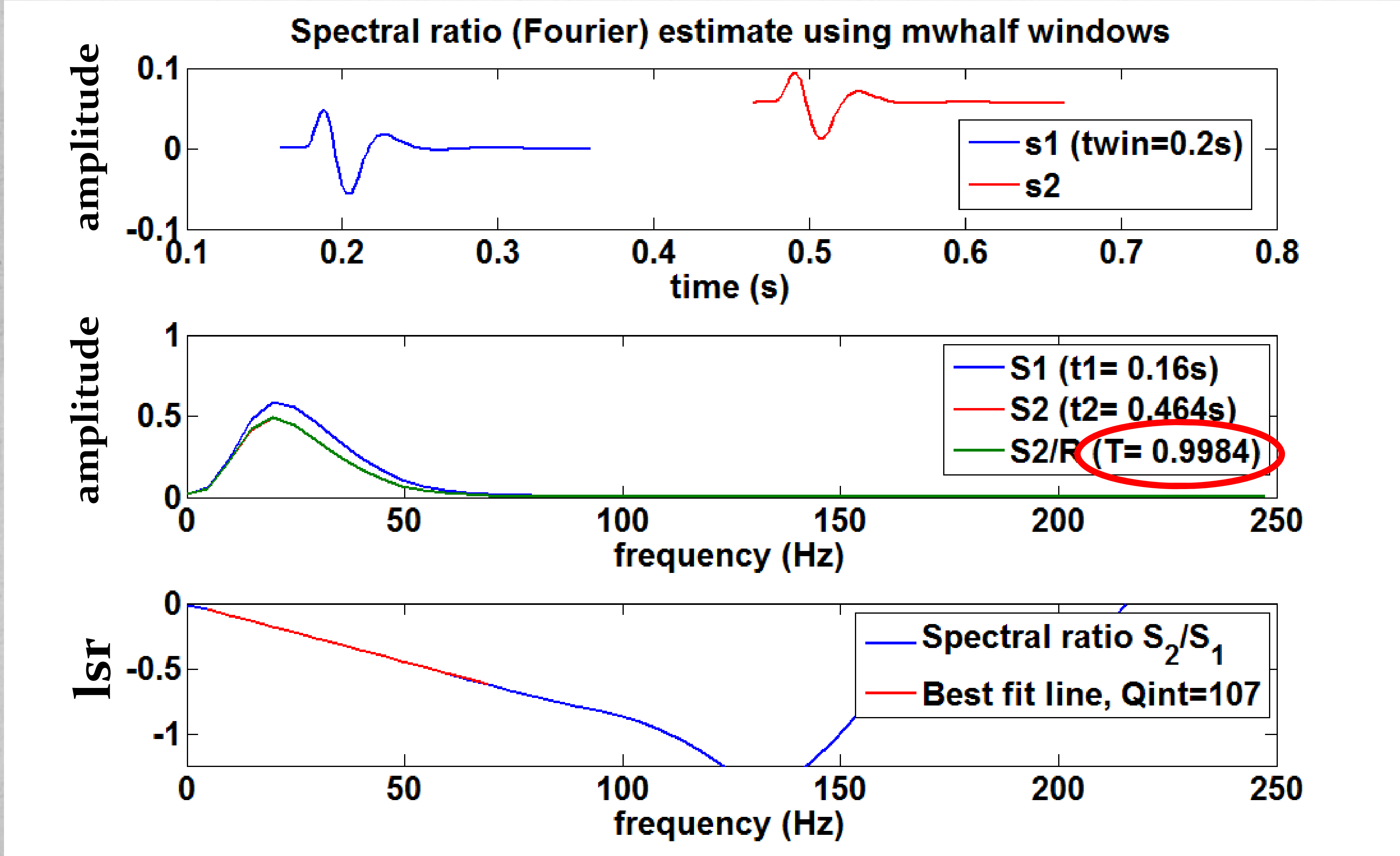
perfect downgoing wavelet



Q estimated by spectral ratio
from perfect downgoing field



Q estimated by spectral ratio
from perfect downgoing field

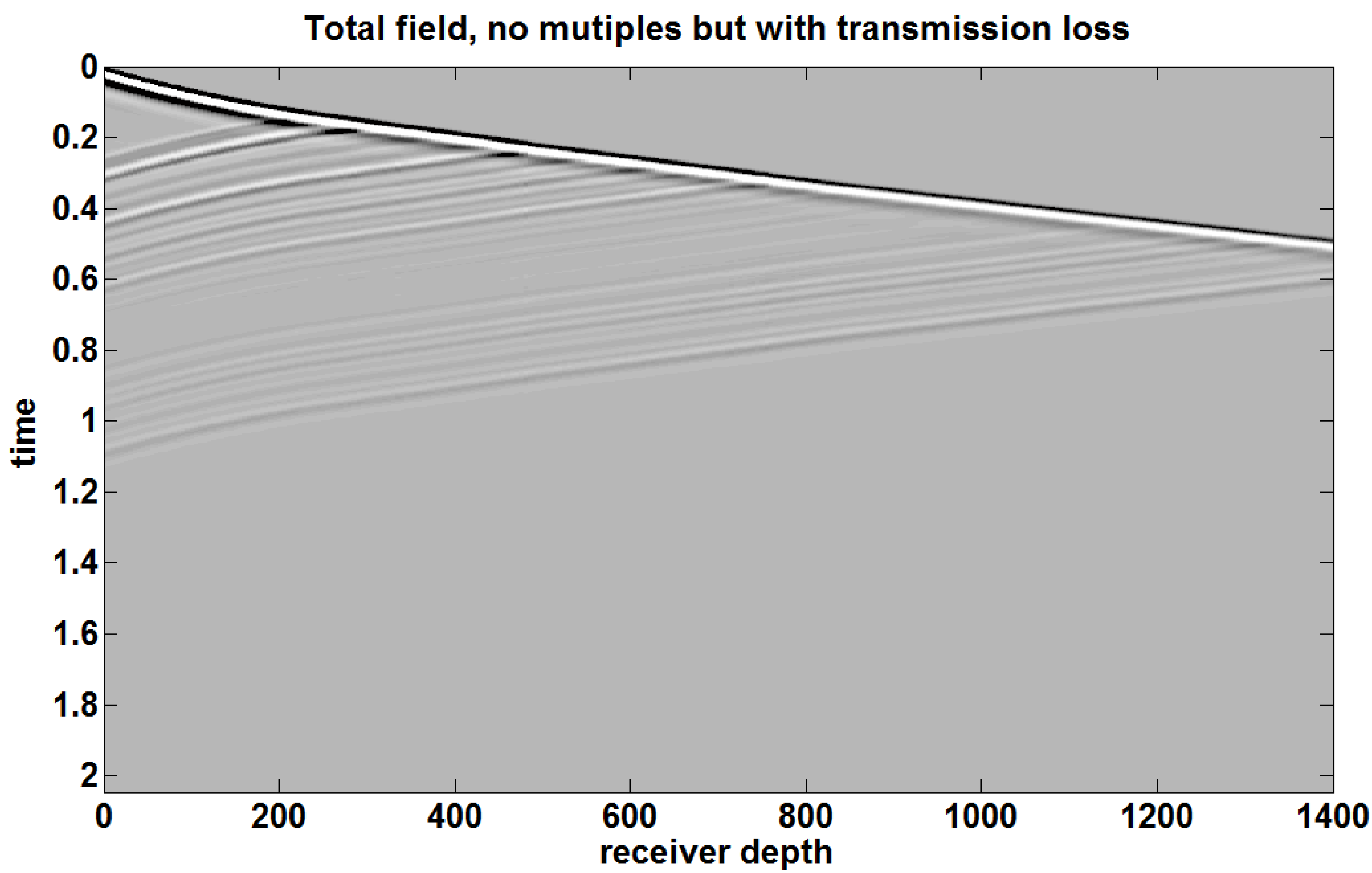


Are transmission effects biasing the estimate?

Run the VSP algorithm with no multiples to produce a downgoing wave with only Q and transmission effects. Measure Q on this wave.

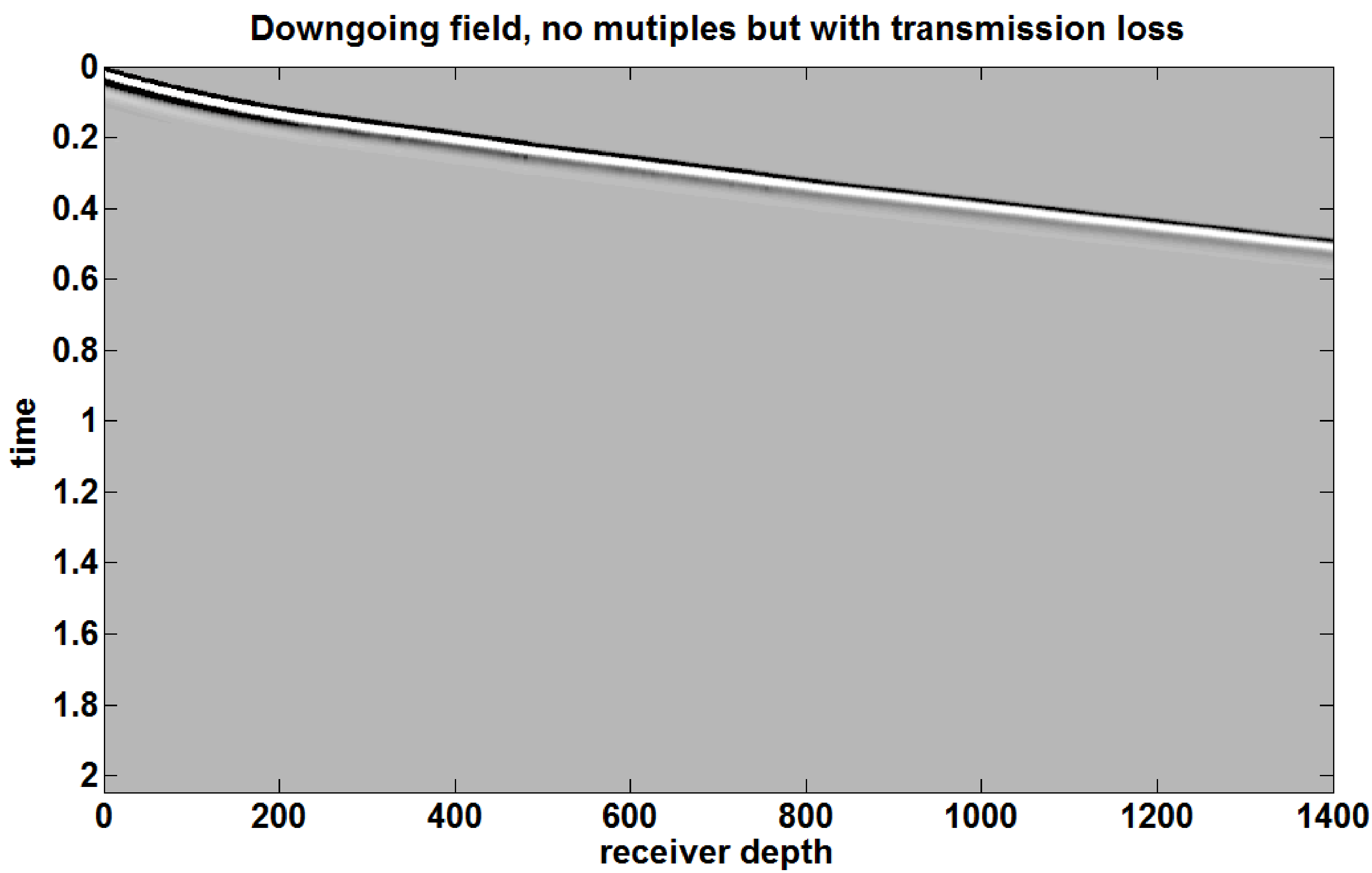
VSPMODELQ

total field, no multiples



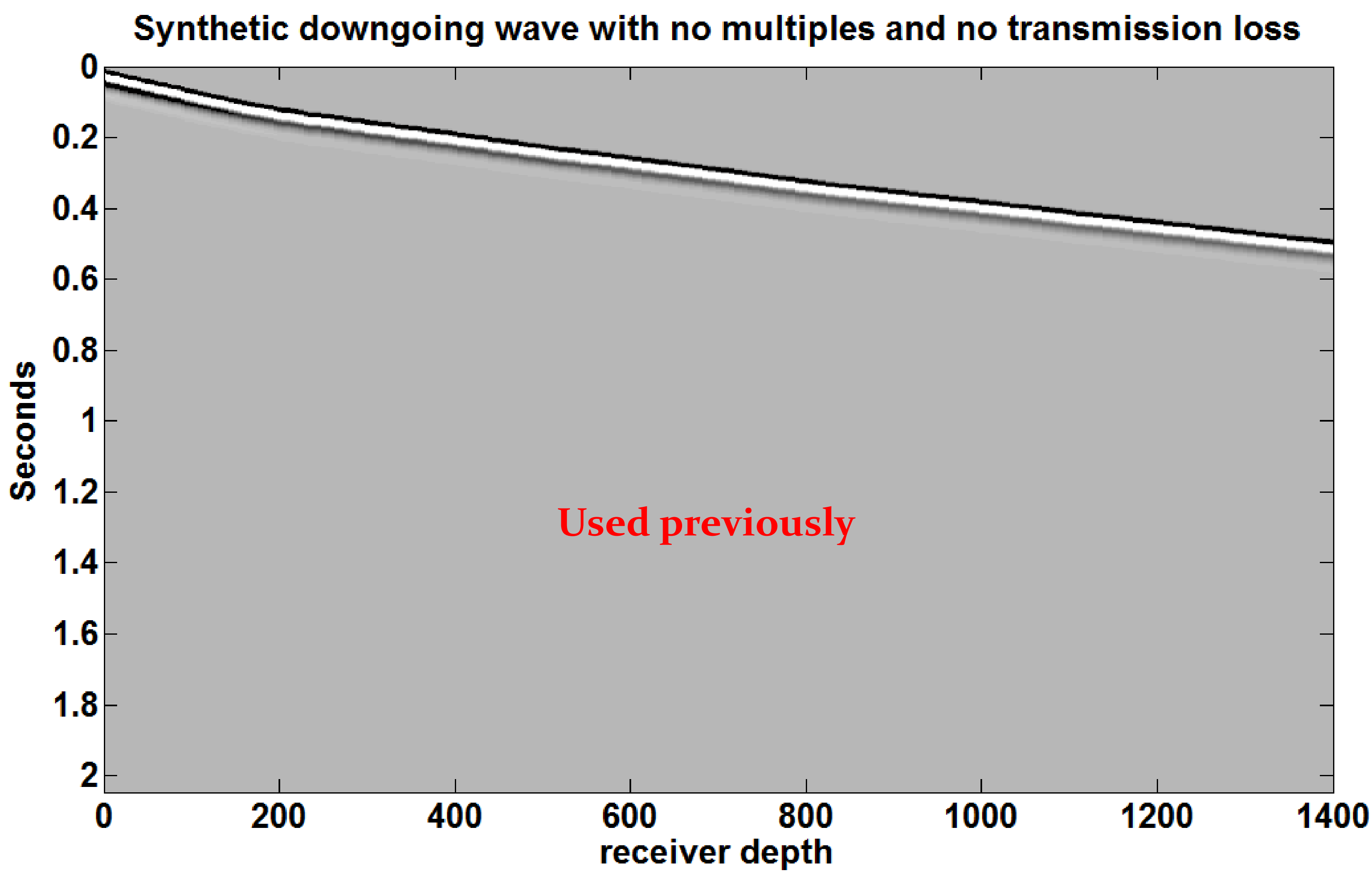
VSPMODELQ

downgoing field, no multiples, transmission loss

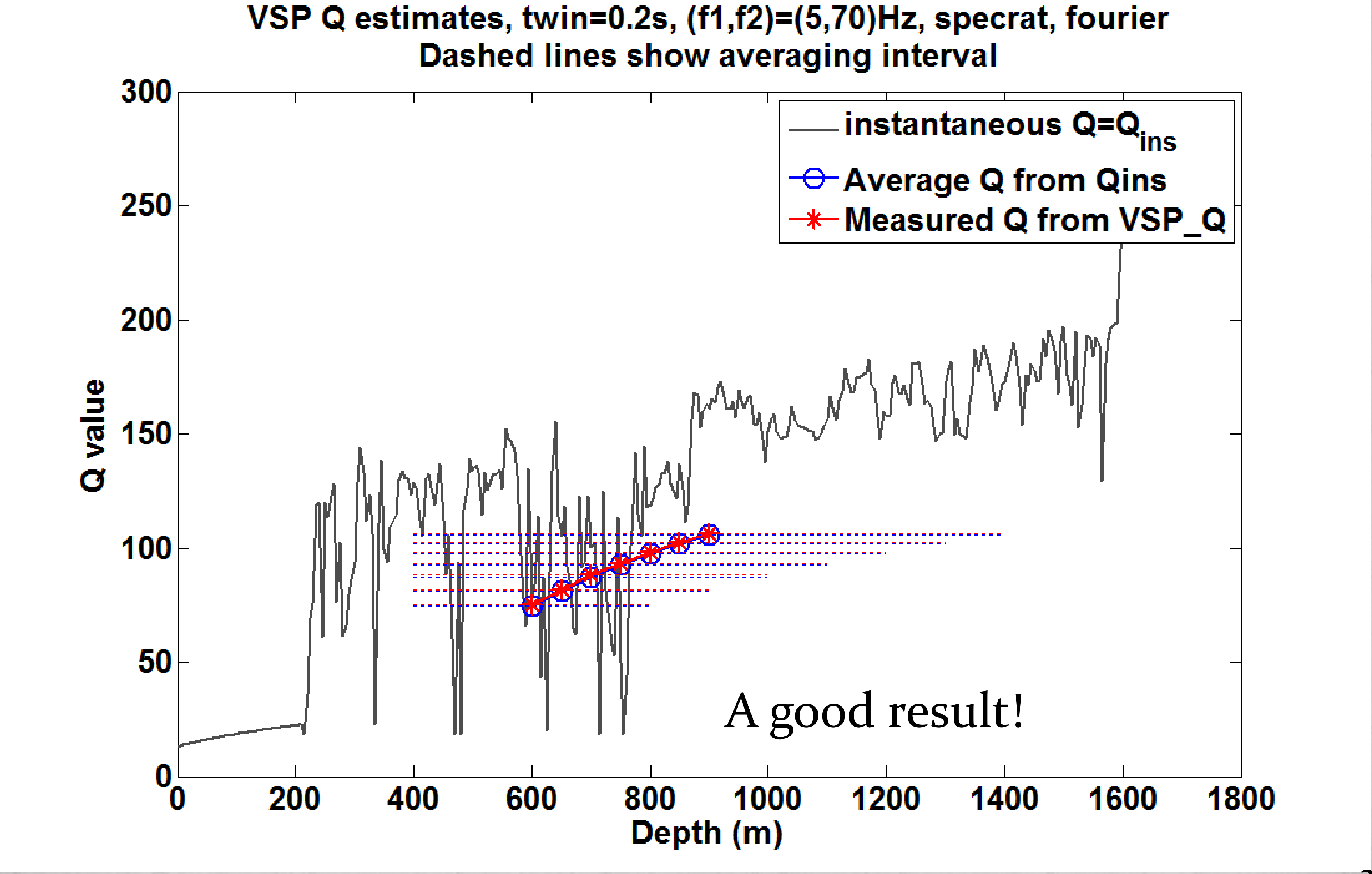


VSPMODELQ

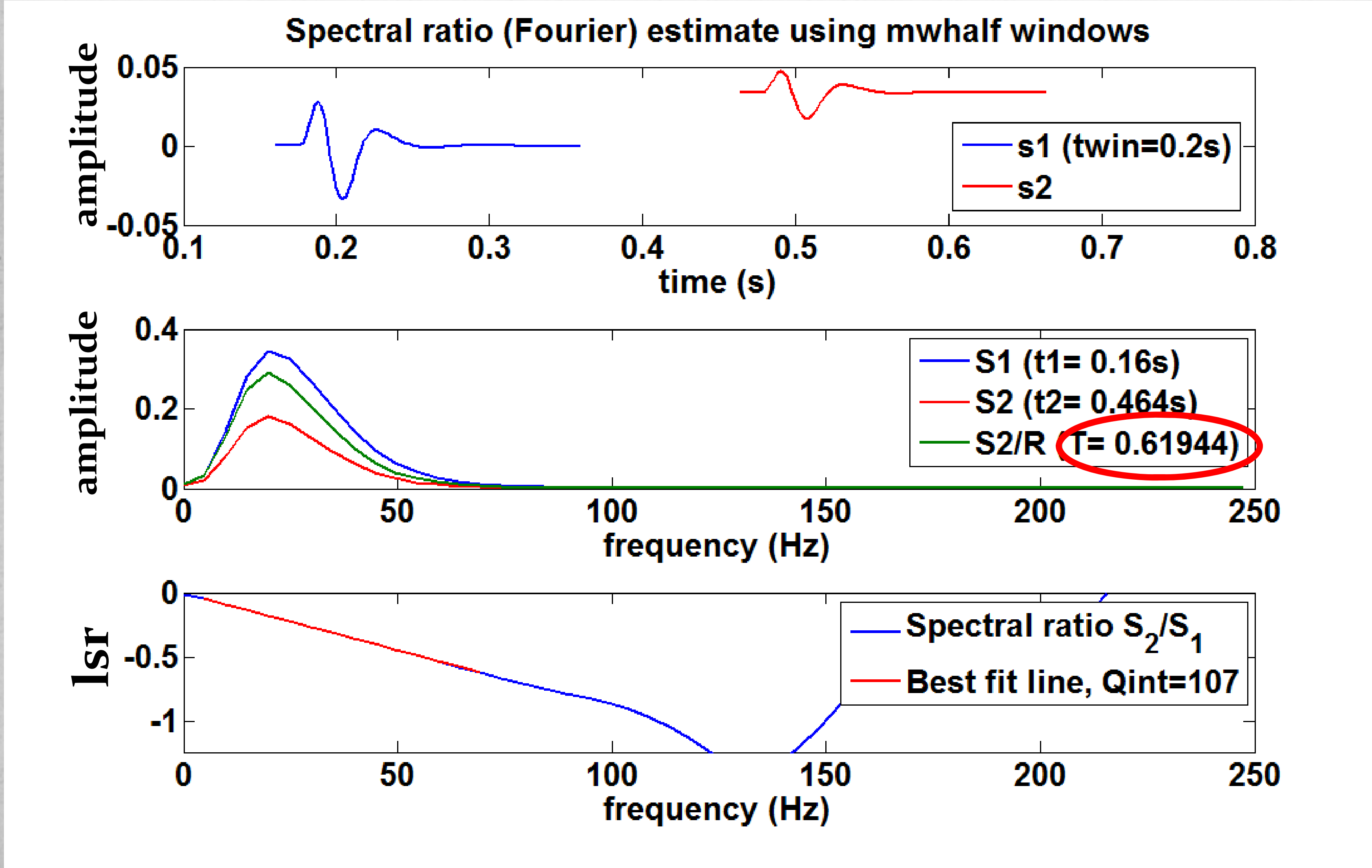
perfect downgoing wavelet



Q estimated by spectral ratio
from downgoing field with transmission loss



Q estimated by spectral ratio
from downgoing field with transmission losses

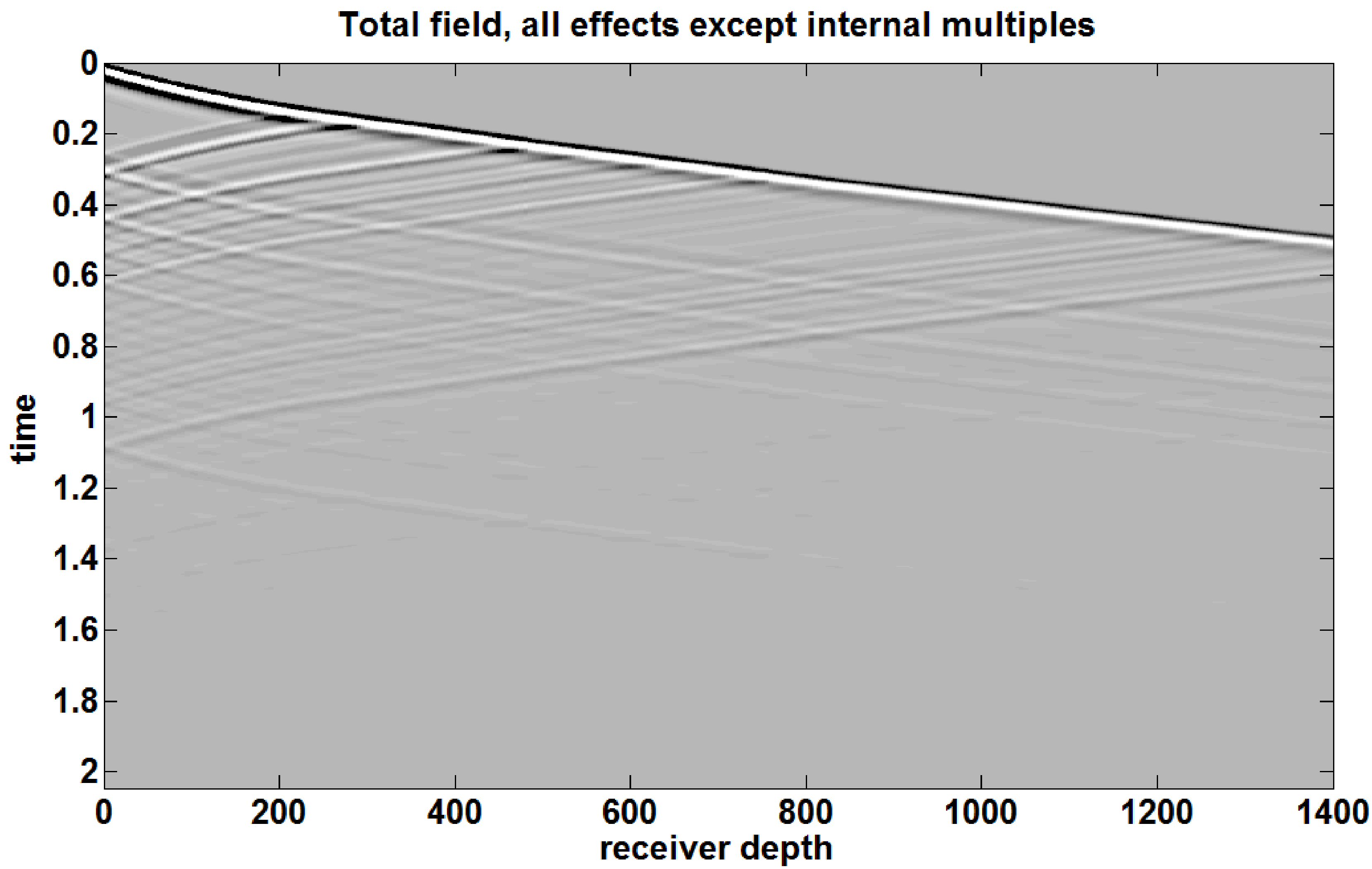


Are surface multiples biasing the estimate?

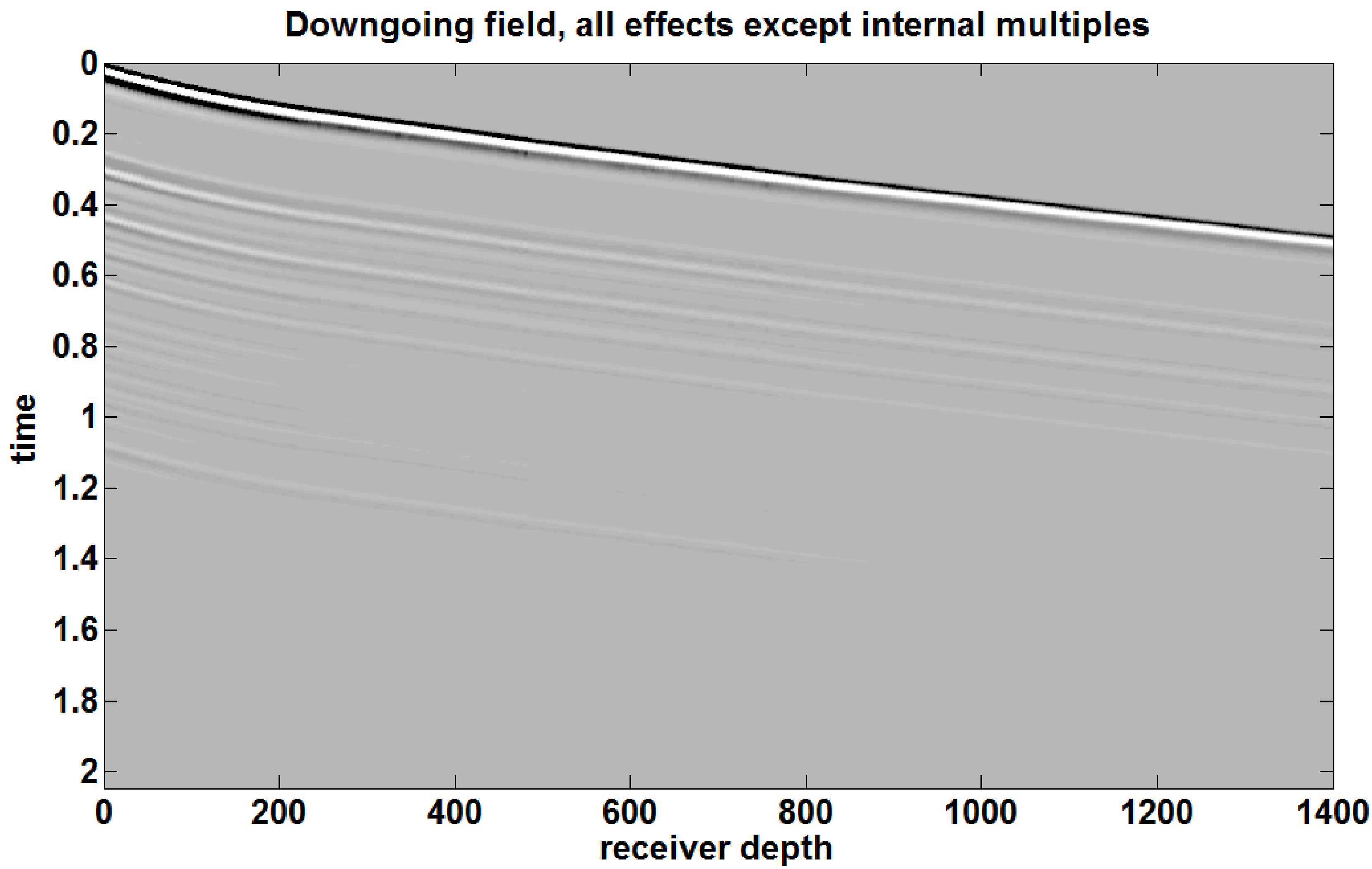
Run the VSP algorithm with surface multiples but no internal multiples to produce a downgoing wave with all effects except internal multiples. Measure Q on this wave.

VSPMODELQ

total field, surface multiples only

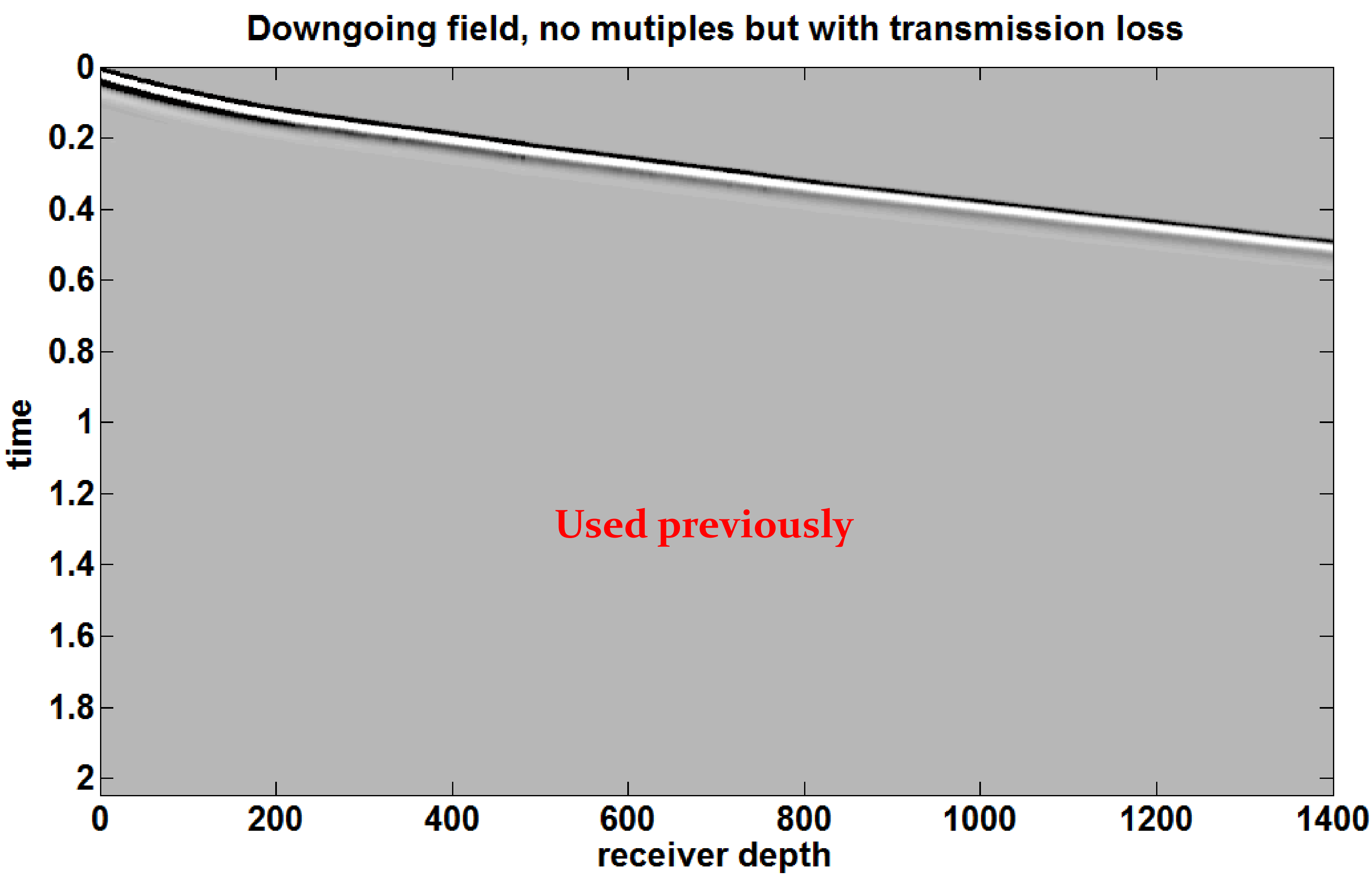


VSPMODELQ
downgoing field surface multiples only

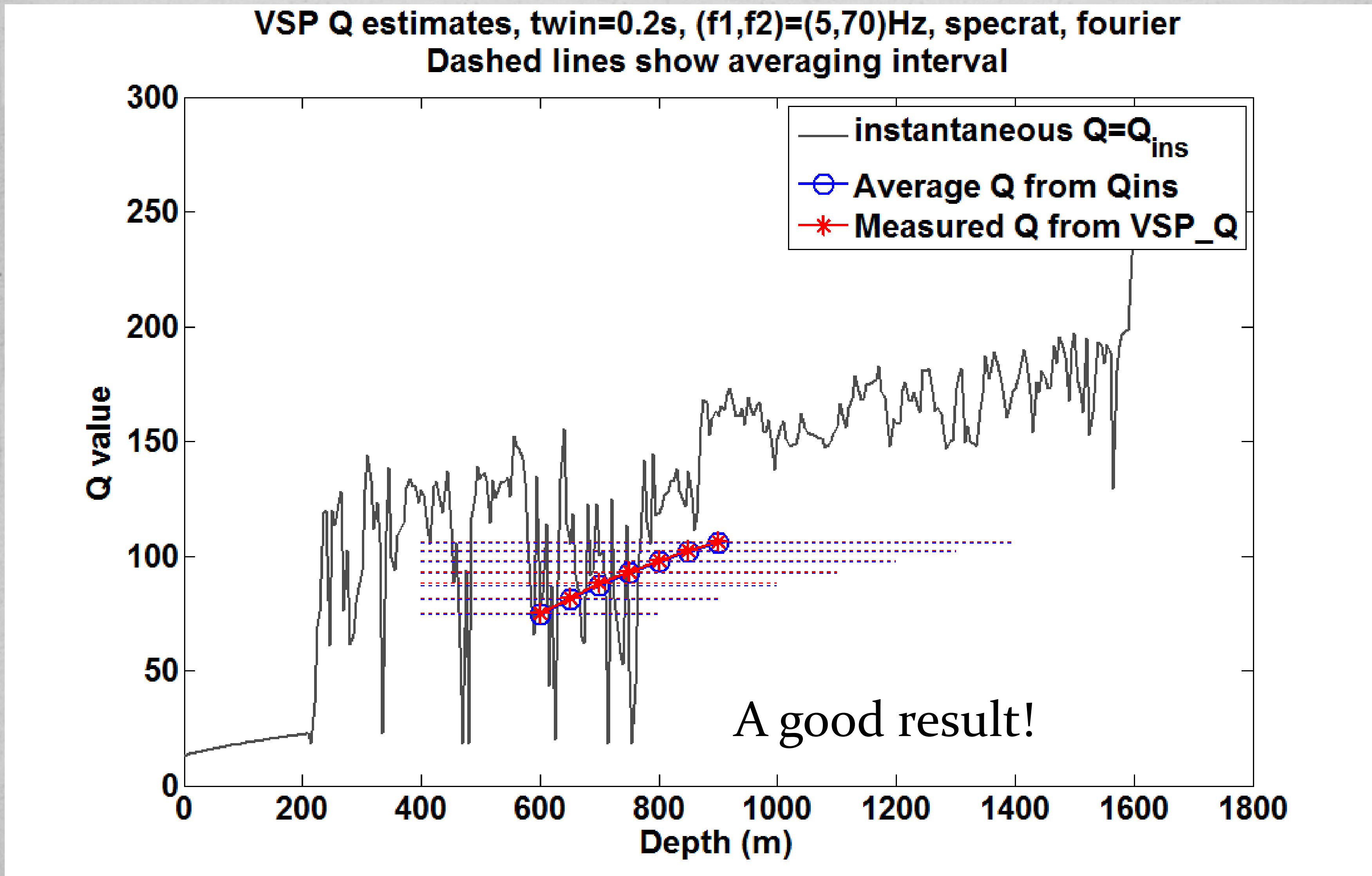


VSPMODELQ

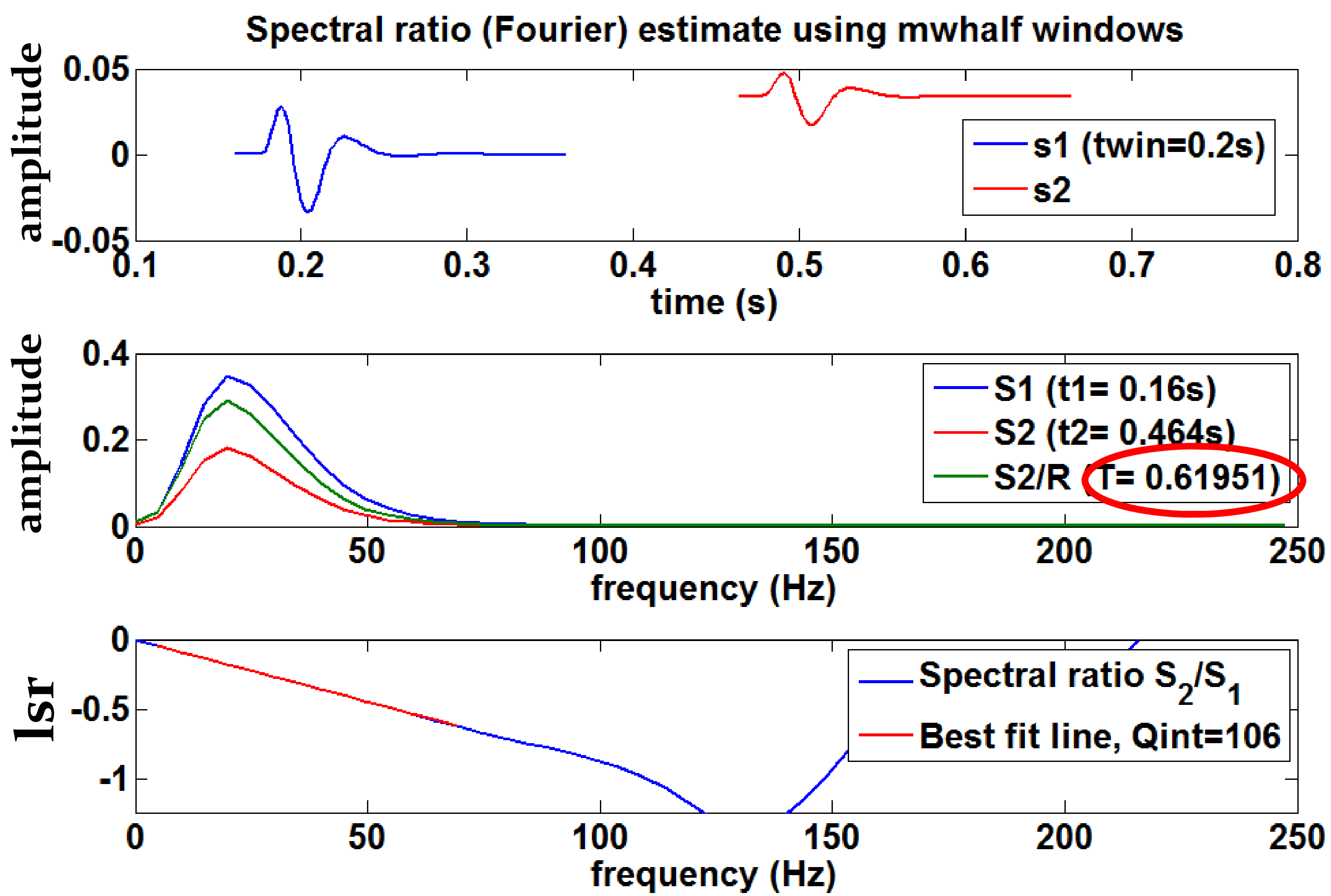
total field, no multiples



Q estimated by spectral ratio
from downgoing field with surface multiples



Q estimated by spectral ratio
from downgoing field with surface multiples

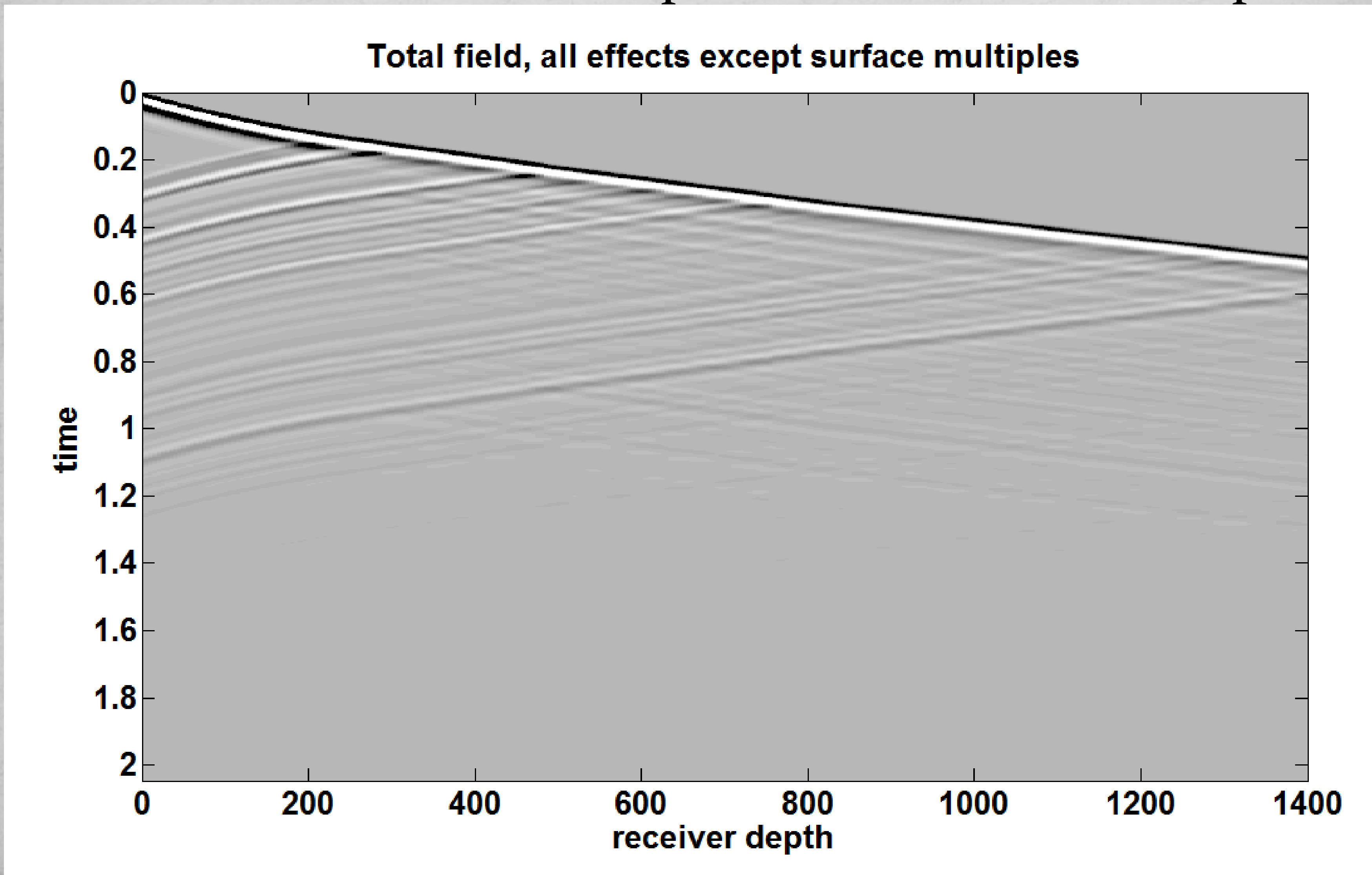


Are internal multiples biasing the estimate?

Run the VSP algorithm with internal multiples but no surface multiples to produce a downgoing wave with all effects except surface multiples. Measure Q on this wave.

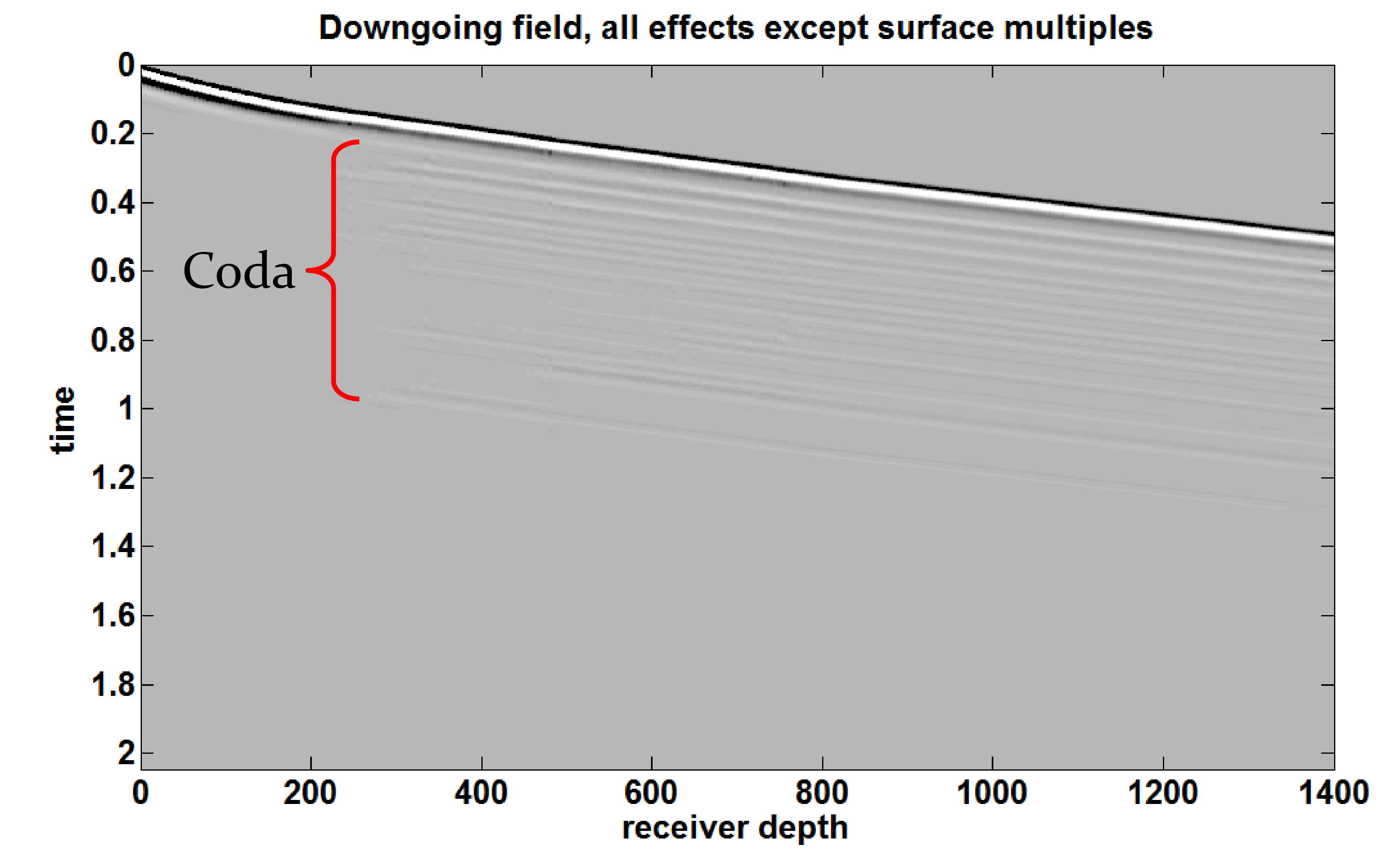
VSPMODELQ

total field, internal multiples but no surface multiples



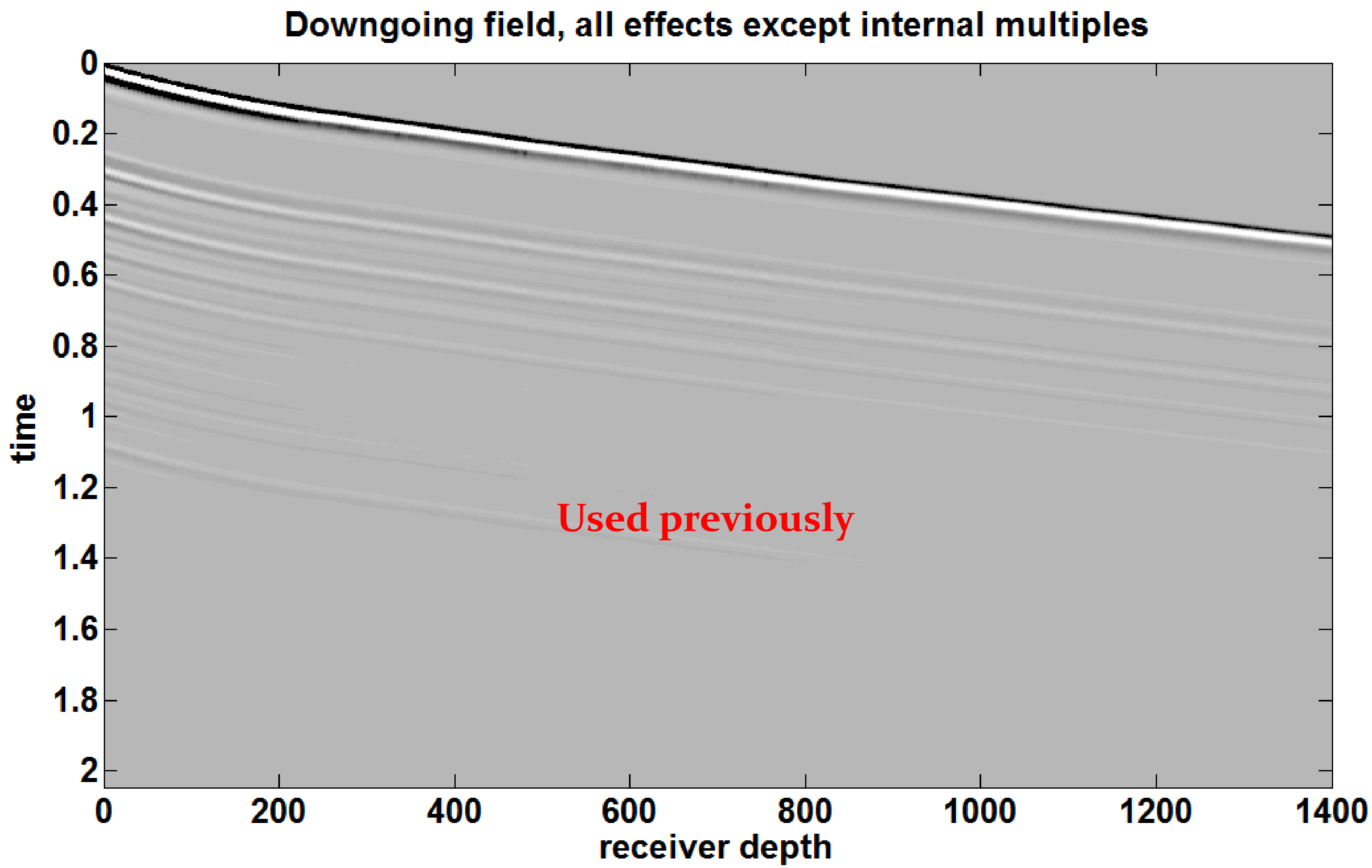
VSPMODELQ

downgoing field, all effects except surface multiples

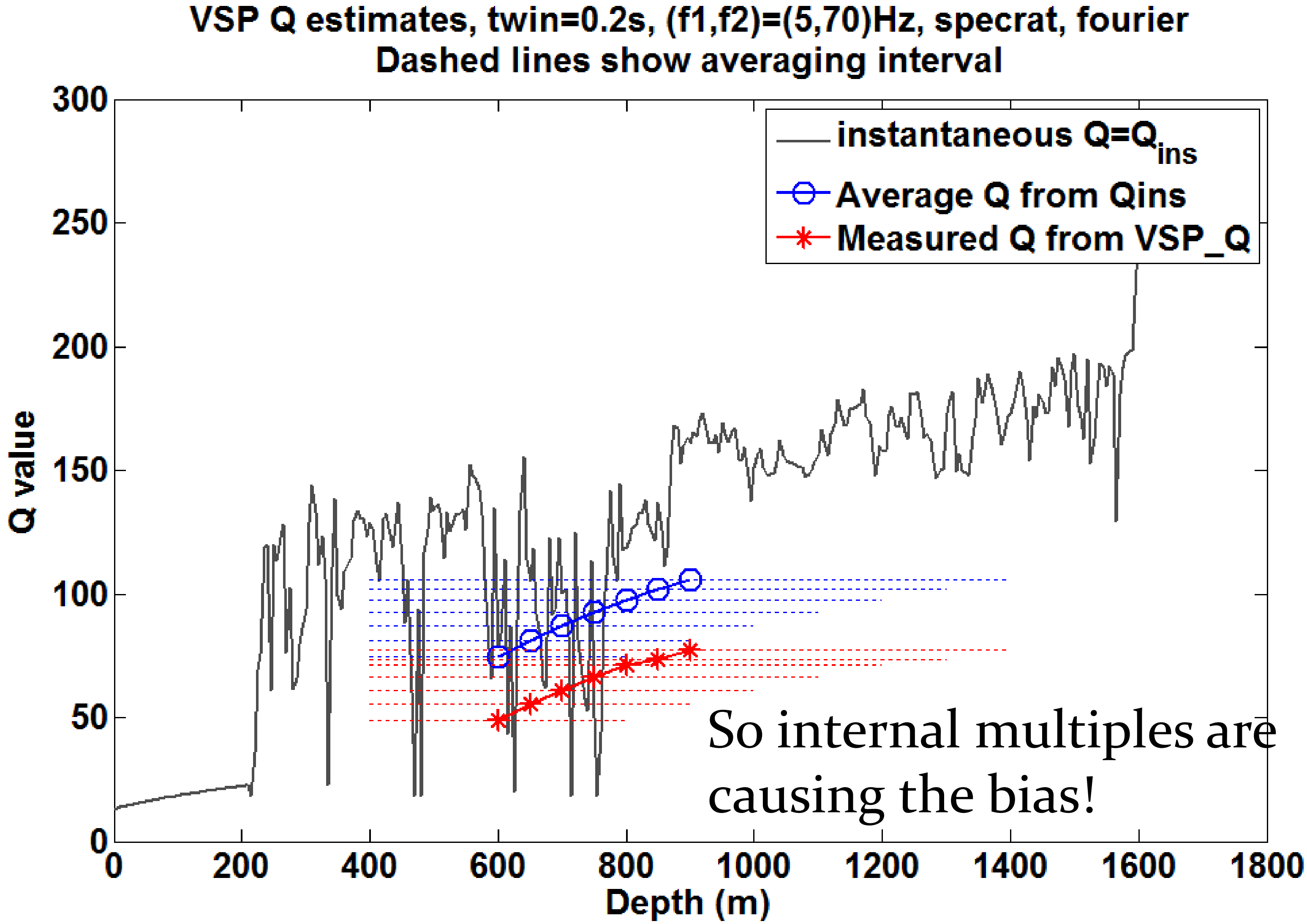


VSPMODELQ

total field, no internal multiples

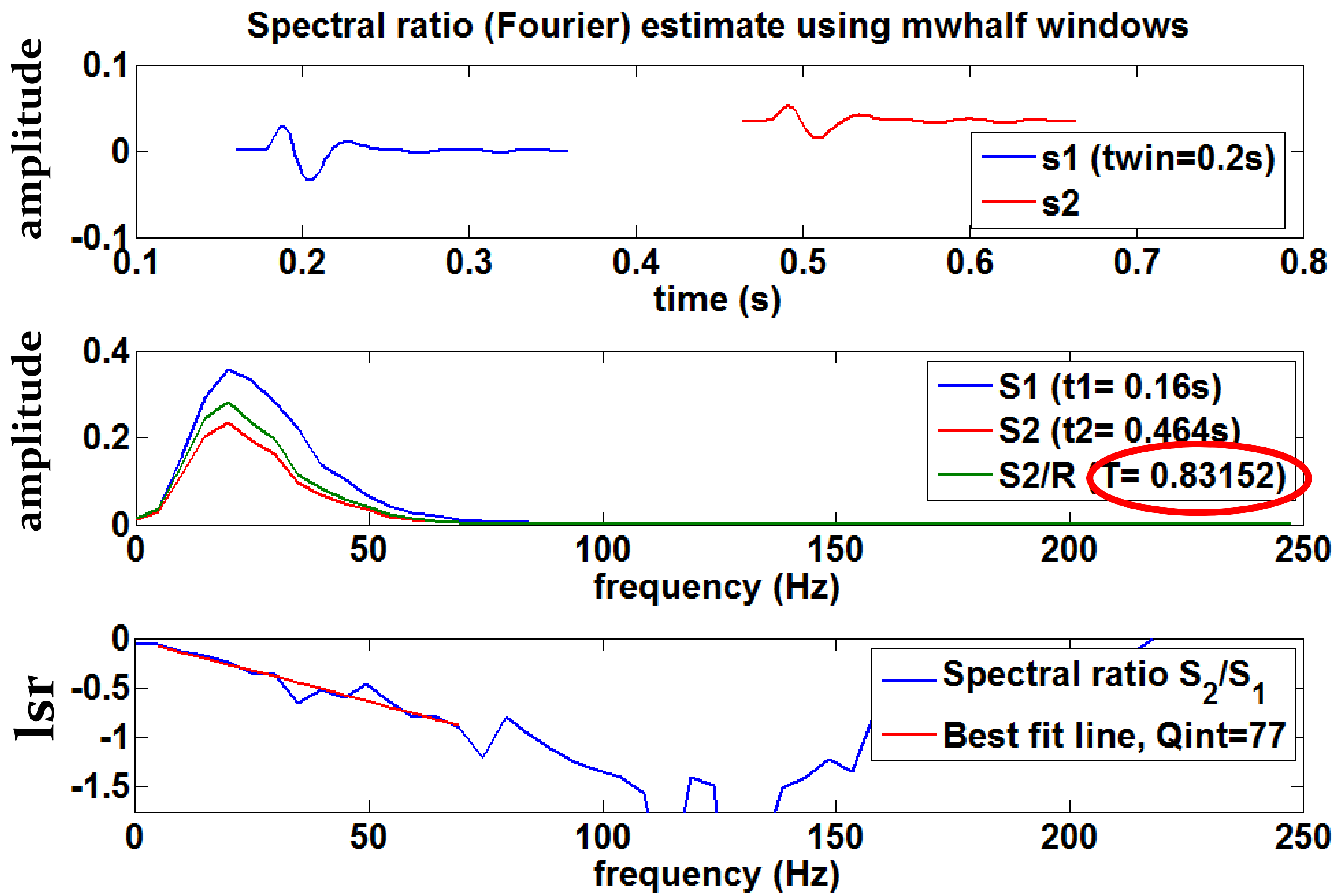


Q estimated by spectral ratio
from downgoing field including internal multiples

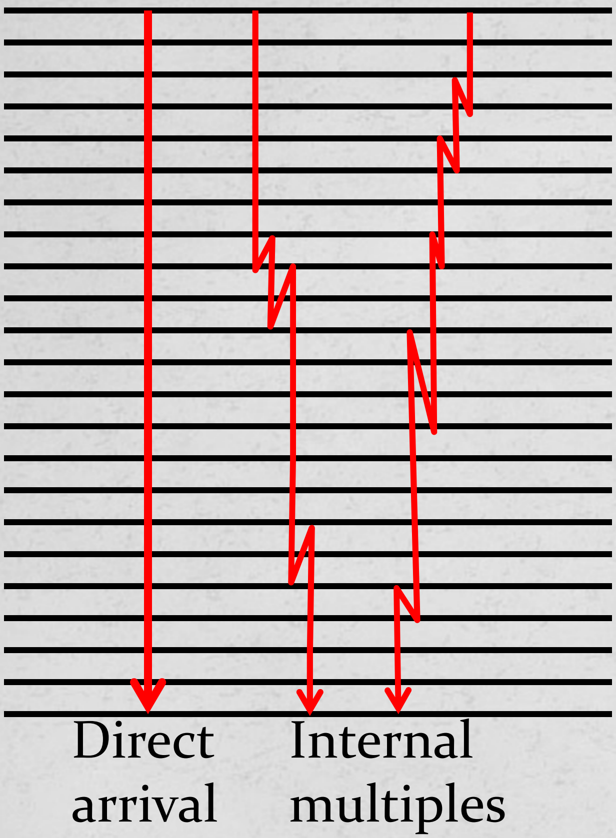


So internal multiples are causing the bias!

Q estimated by spectral ratio
from downgoing field with internal multiples



Stratigraphic filtering



As first discussed by O'Doherty and Anstey[1], <u>a wave propagating through a finely layered elastic medium displays an apparent Q due to the interference of the internal multiples following the direct wave.</u> Similarly, a finely layered anelastic medium will show an increased attenuation effect due to the internal multiples.

There is one unique direct arrival but infinitely many internal multiples. We expect the internal multiples to have greater traveltime, greater attenuation, and greater total energy than the direct arrival.

[1]O'Doherty, R. F., and N. A. Anstey, 1971, *Reflections on Amplitudes*, Geophysical Prospecting, 19.

Stratigraphic filtering

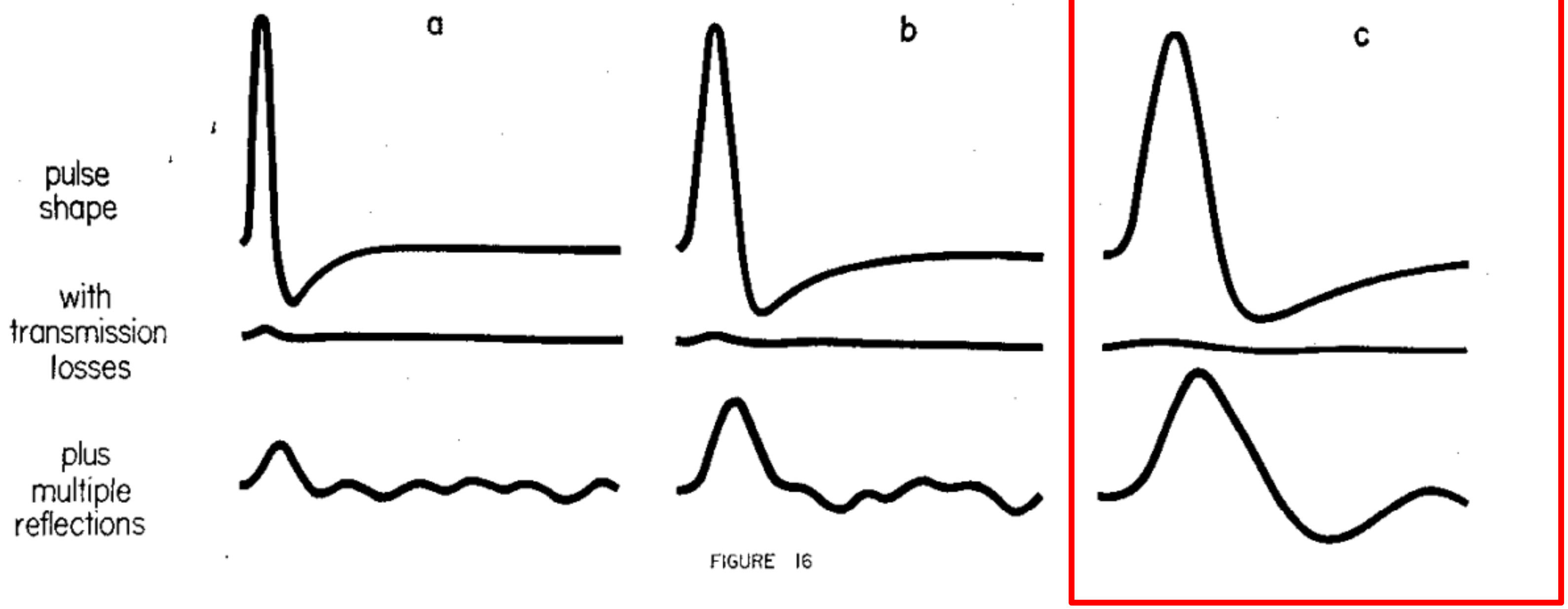


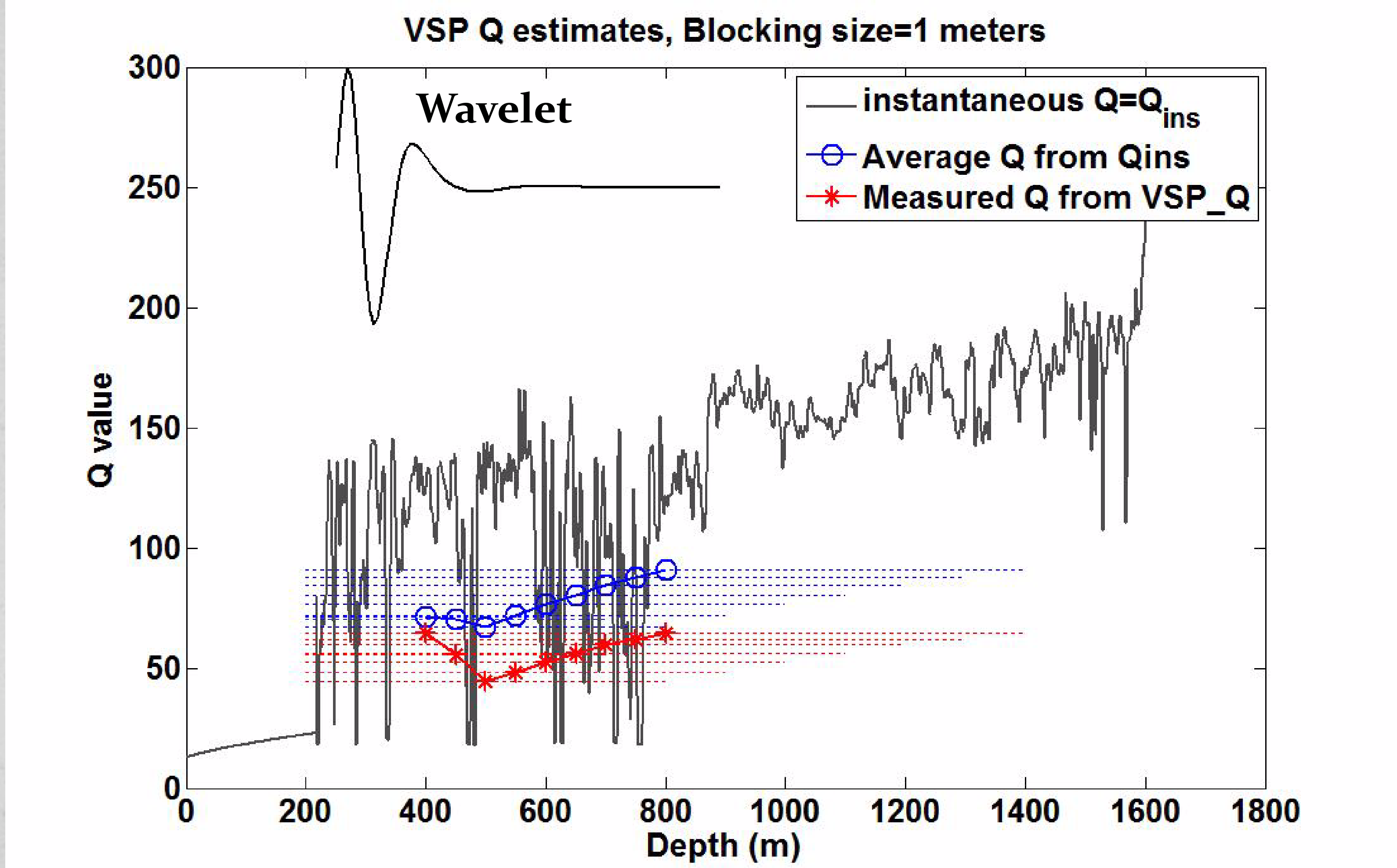
Fig. 16. The effect of convolving three seismic pulse shapes transmission through the log of fig. 12, without and with the e multiple reflections.

Note the decrease of dominant frequency

From: O'Doherty and Anstey, 1971, *Reflections on Amplitudes*, Geophysical Prospecting, 19

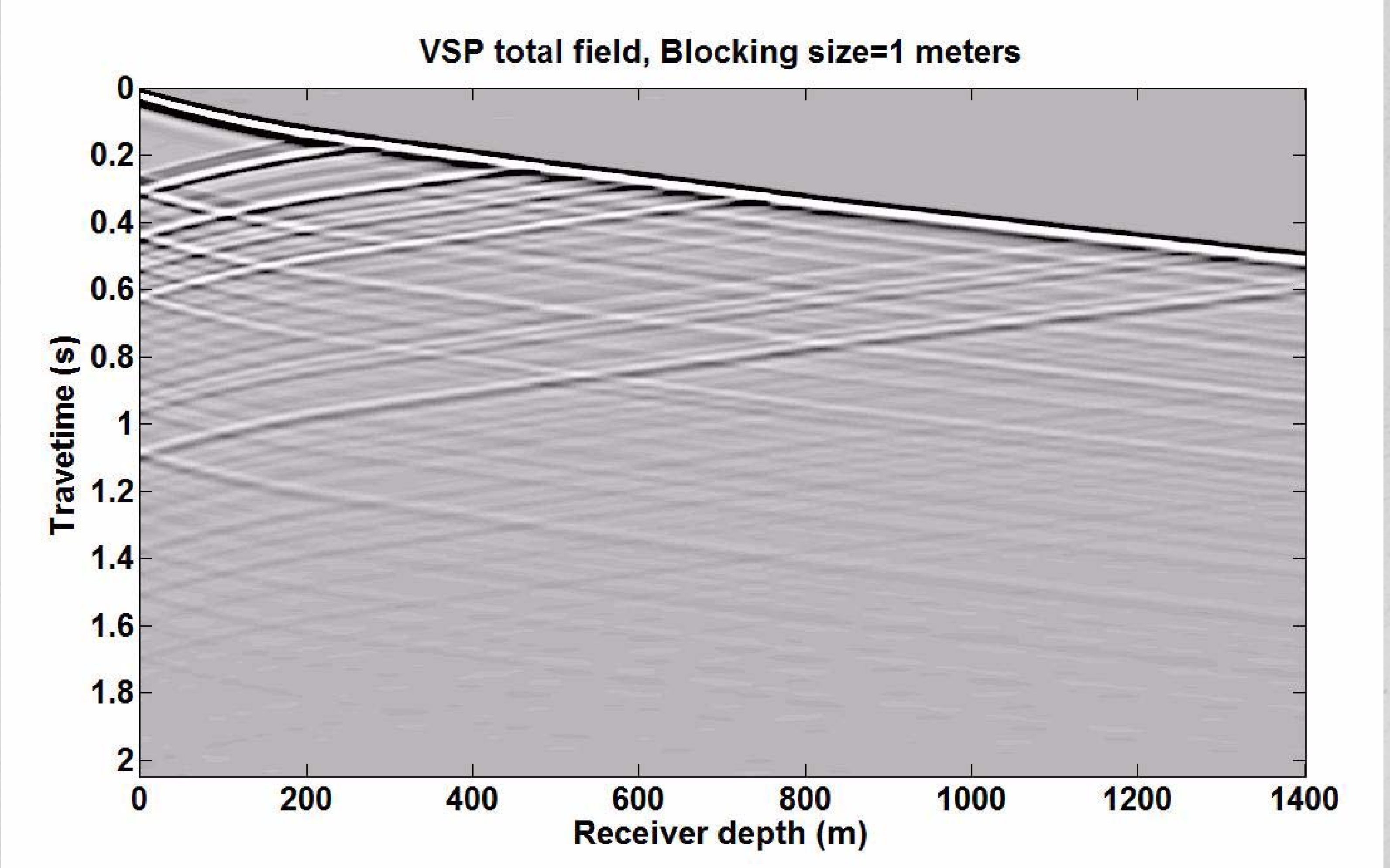
Stratigraphic filtering

movie



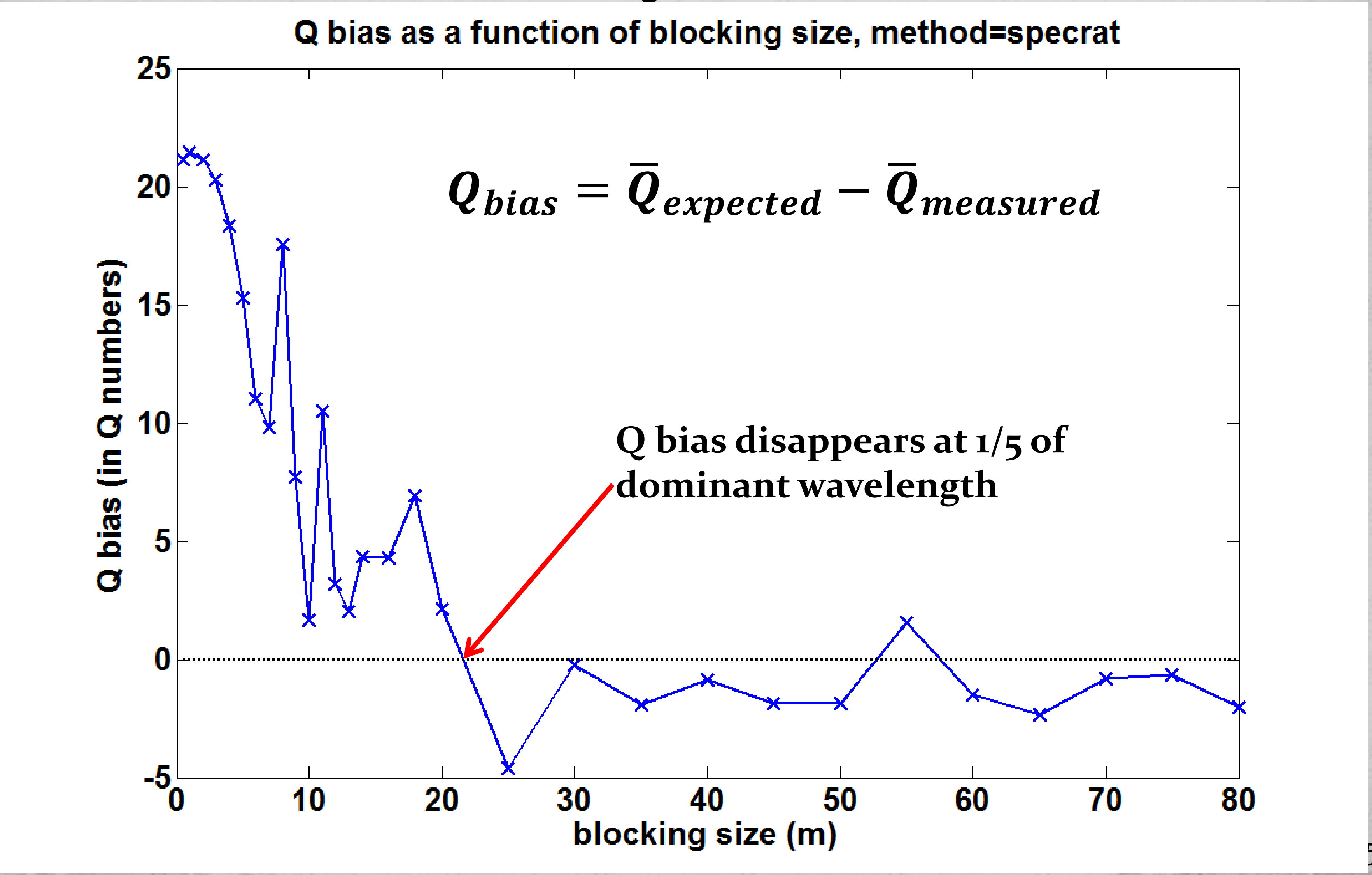
Stratigraphic filtering

movie



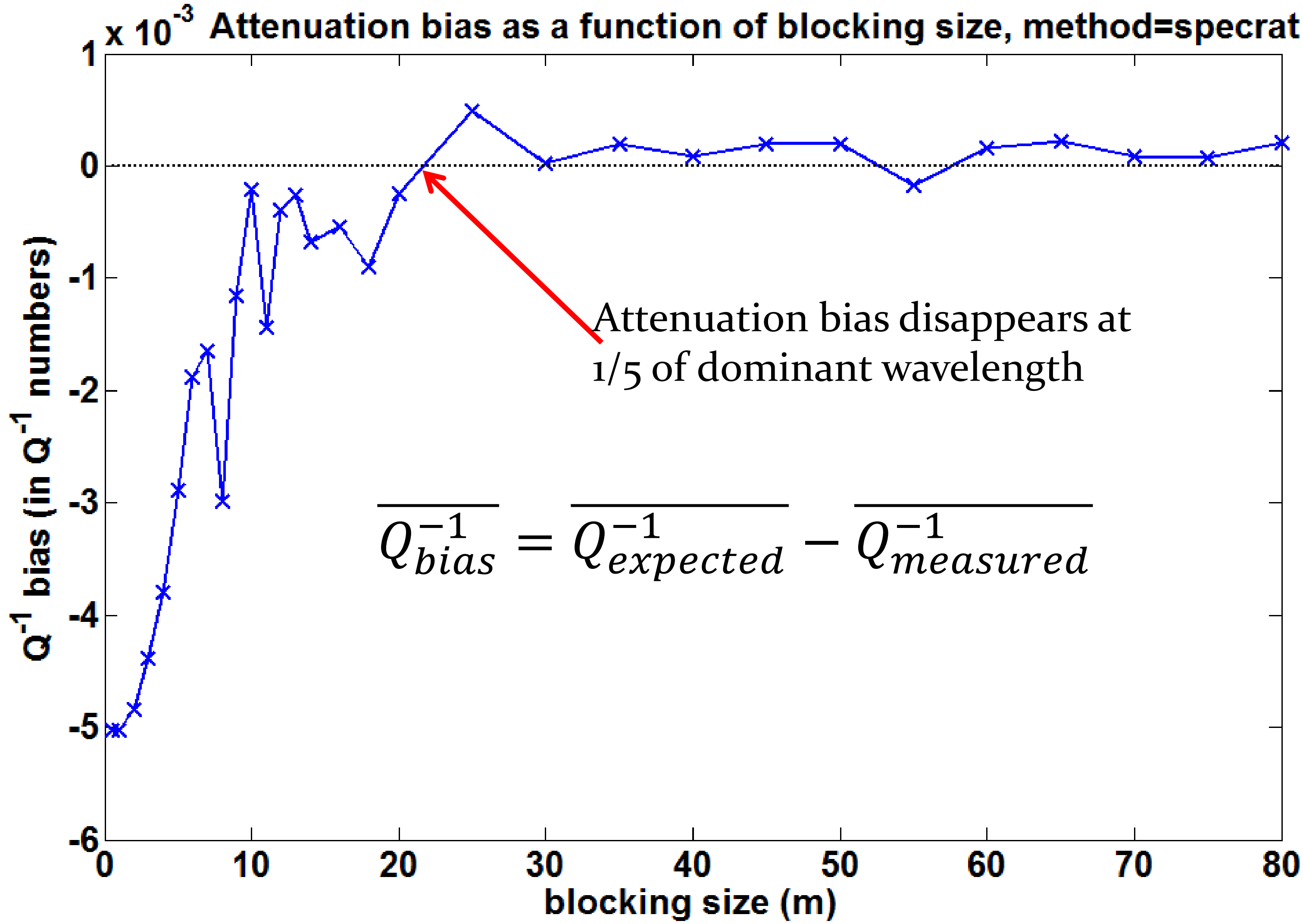
Stratigraphic filtering

Q bias



Stratigraphic filtering

Q^{-1} *bias*



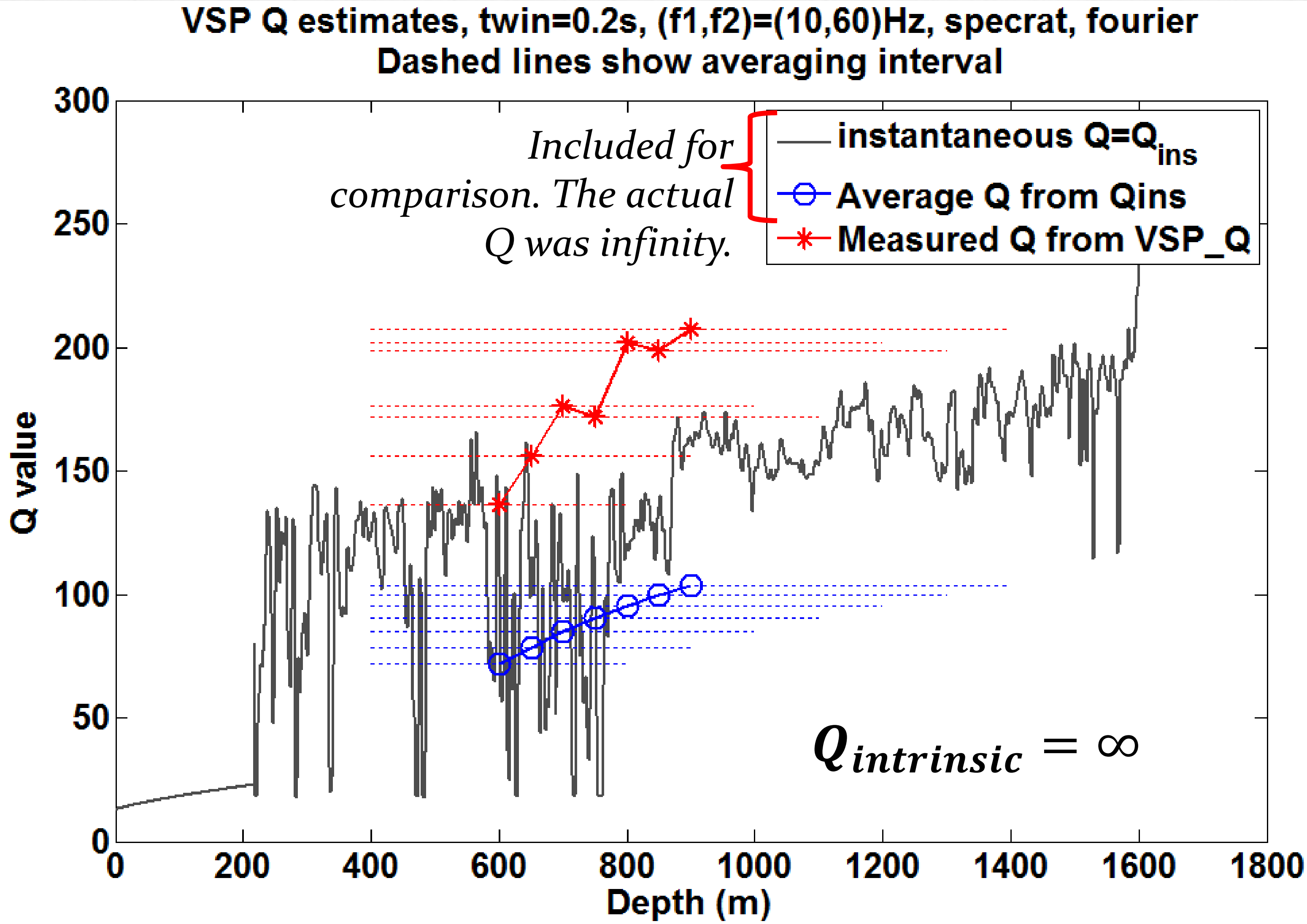
$$\overline{Q^{-1}_{bias}} = \overline{Q^{-1}_{expected}} - \overline{Q^{-1}_{measured}}$$

Direct measurement of Q_{strat}

Run the VSP algorithm with no intrinsic attenuation ($Q_{int} = \infty$). Any measurable attenuation will be a direct measurement of Q_{strat}.

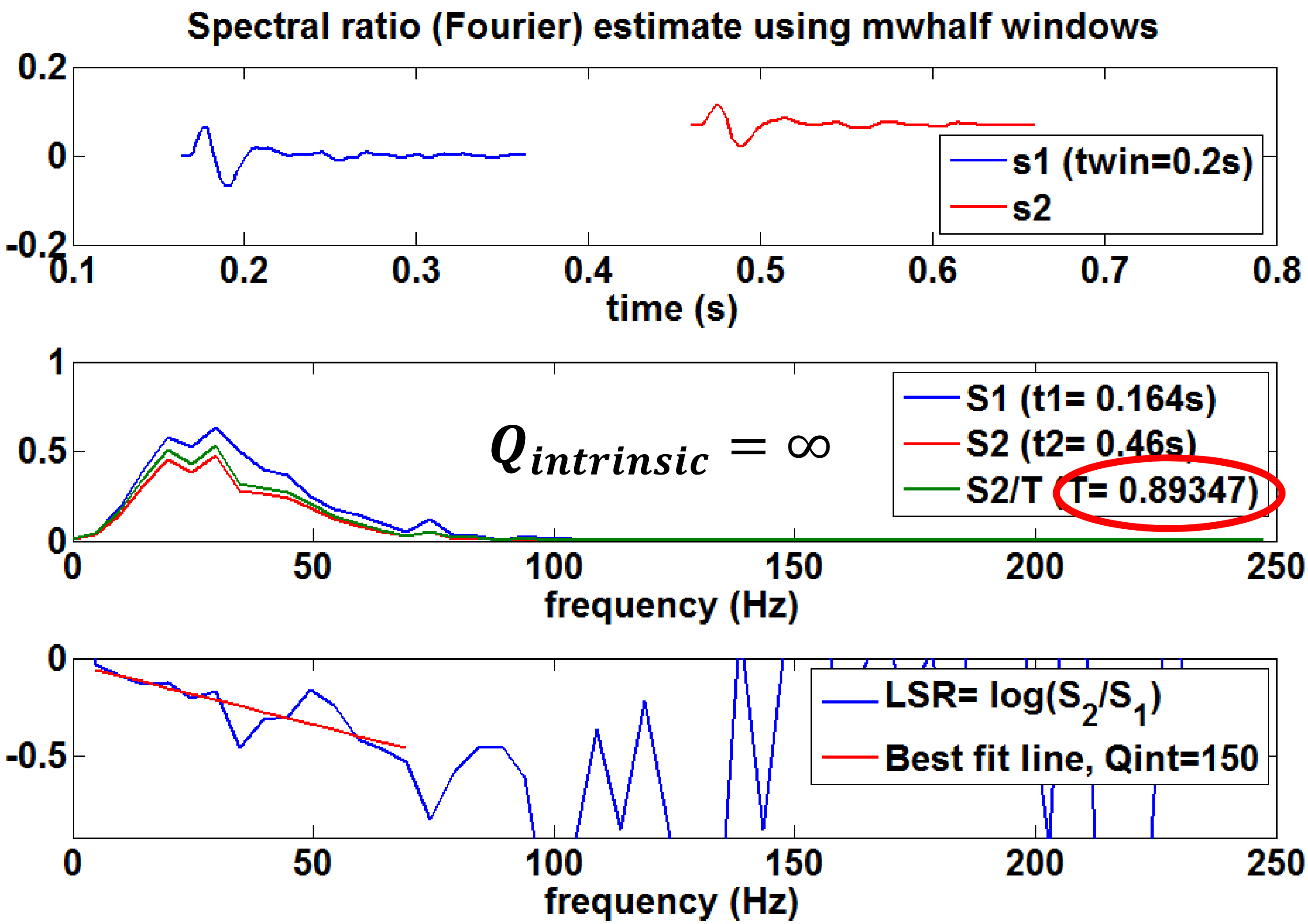
Direct measurement of Q_{strat}

Stratigraphic filtering



Direct measurement of Q_{strat}

Q estimated by spectral ratio



Direct measurement of Q_{strat}

Does the measured Q_{strat} agree with the previous results? If so then we expect the following to be true[1]:

$$\frac{1}{Q_{eff}} = \frac{1}{Q_{intrinsic}} + \frac{1}{Q_{strat}}$$

Measured previously

Prescribed in model

Measured with $Q = \infty$ in model

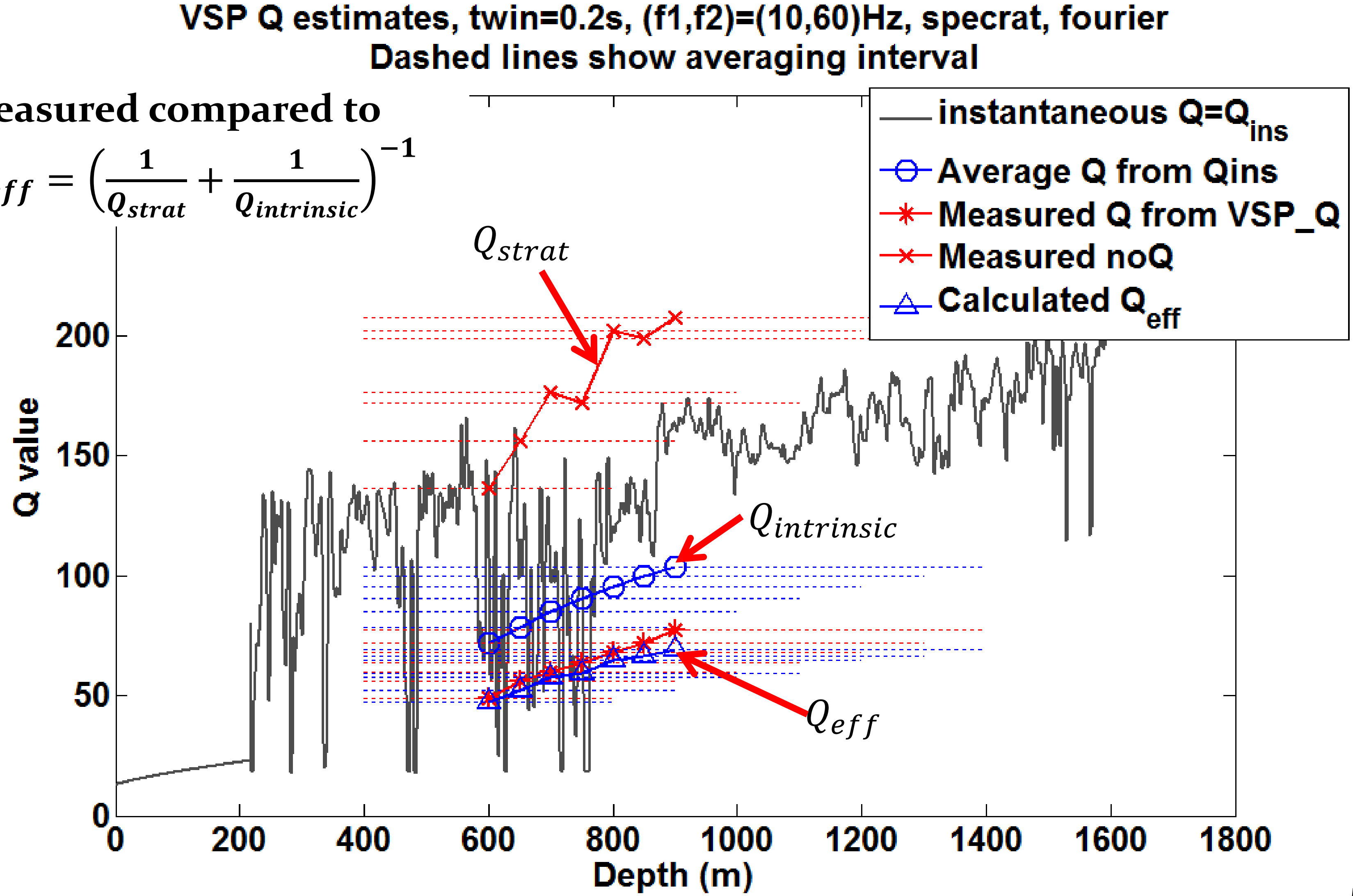
[1]Richards and Menke, 1983, *The Apparent attenuation of a scattering medium*, BSSA, 73.

Direct measurement of Q_{strat}

consistency of measurements

Measured compared to

$$Q_{eff} = \left(\frac{1}{Q_{strat}} + \frac{1}{Q_{intrinsic}}\right)^{-1}$$



Conclusions

- A 1-D synthetic VSP algorithm that includes the effects of internal multiples, surface multiples, and anelastic attenuation has been created and released.
- Q measurements on synthetic VSP's created from well logs are consistently biased to lower values than the intrinsic Q.
- This bias is due to internal multiples that create a complex coda following the direct wave.
- Analysis shows that the bias only appears for log blocking sizes smaller than about 10 m.
- Most Q estimation methods will show this bias.

CREWES

Acknowledgements

My thanks to all CREWES sponsors for supporting this research. Thanks also the NSERC, CMC, and the UofC for additional support. Special thanks to P.F. Daley, Kris Innanen, and Don Lawton for helpful discussions.

This work was supported by NSERC grants CDPRJ 379744-08 and RGPIN 217032-2013.

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NSERC CRSNG

The VSP problem

Displacement and pressure solutions

If $R = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}$ is the reflection coefficient for incidence from above, then the displacement reflection is given by

$$U = -RD$$ **Displacement Law**

where D is the incident downgoing displacement .

For pressure the reflection law is

$$U_{press} = RD_{press}$$ **Pressure Law**

The minus sign in the displacement law accounts for the reversal of direction of the displacement.

So, given a code that computes a displacement solution, we can obtain a pressure solution by replacing R by $-R$ in all reflection expressions.

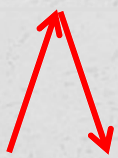
Extreme boundaries
free surface, incidence from below

Free surface. Let R^+ be the reflection coefficient for incidence from above.

Then $R^+ = \frac{v_2\rho_2 - v_1\rho_1}{v_2\rho_2 + v_1\rho_1} = +1$. For incidence from below $R^- = -R^+ = -1$. For a P wave incident from below, the displacement reflection is $u_R^- = -R^- u_{inc} = u_{inc}$ while the pressure is $p_R^- = R^- p_{inc} = -p_{\text{inc}}$.

Velocity = $v_1 = 0$
Density = $\rho_1 = 0$

Velocity = v_2
Density = ρ_2



	Displacement	Pressure
Reflection	$u_R^- = u_{inc}$	$p_R^- = -p_{\text{inc}}$
Total field	$u_R^- + u_{inc} = 2u_{inc}$	$p_R^- + p_{inc} = 0$

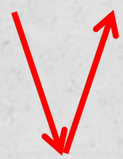
At a free surface, pressure vanishes while displacement doubles.

More generally, if $R^+ > 0$, then for a wave incident from below, pressure changes sign on reflection while displacement does not.

Extreme boundaries
perfectly rigid medium, incidence from above

Rigid layer. Let R^+ be the reflection coefficient for incidence from above. Then $R^+ = \frac{v_2\rho_2 - v_1\rho_1}{v_2\rho_2 + v_1\rho_1} = +1$. For a P wave incident from above, the displacement reflection is $u_R^+ = -R^+ u_{inc} = -u_{inc}$ while the pressure is $p_R^+ = R^+ p_{inc} = p_{\mathrm{inc}}$.

Velocity = v_1
Density = ρ_1



Velocity = $v_2 = \infty$
Density = $\rho_2 = \infty$

	Displacement	Pressure
Reflection	$u_R^+ = -u_{inc}$	$p_R^+ = p_{\mathrm{inc}}$
Total field	$u_R^+ + u_{inc} = 0$	$p_R^- + p_{inc} = 2p_{inc}$

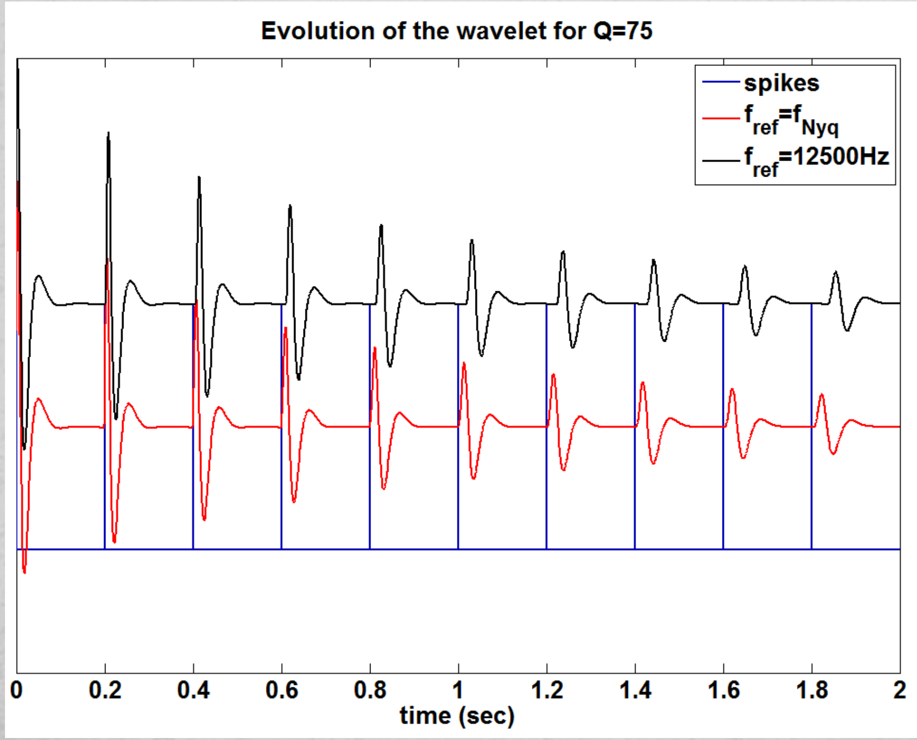
At a rigid boundary, pressure doubles while displacement vanishes.

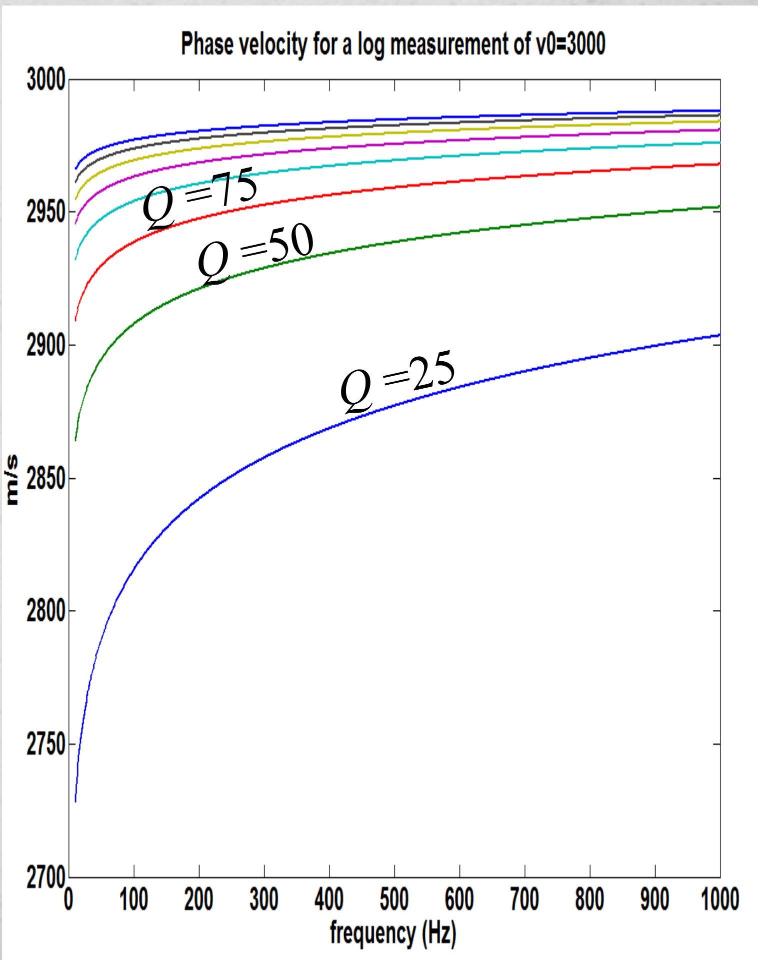
More generally, if $R^+ > 0$, then for a wave incident from above, displacement changes sign on reflection while pressure does not.

Wavelet evolution and drift

Frequency dependent phase velocity → "drift" and wavelet shape.

$$v(f) = v(f_{ref})\left(1 + \frac{1}{\pi Q}\log\left(\frac{f}{f_{ref}}\right)\right)$$

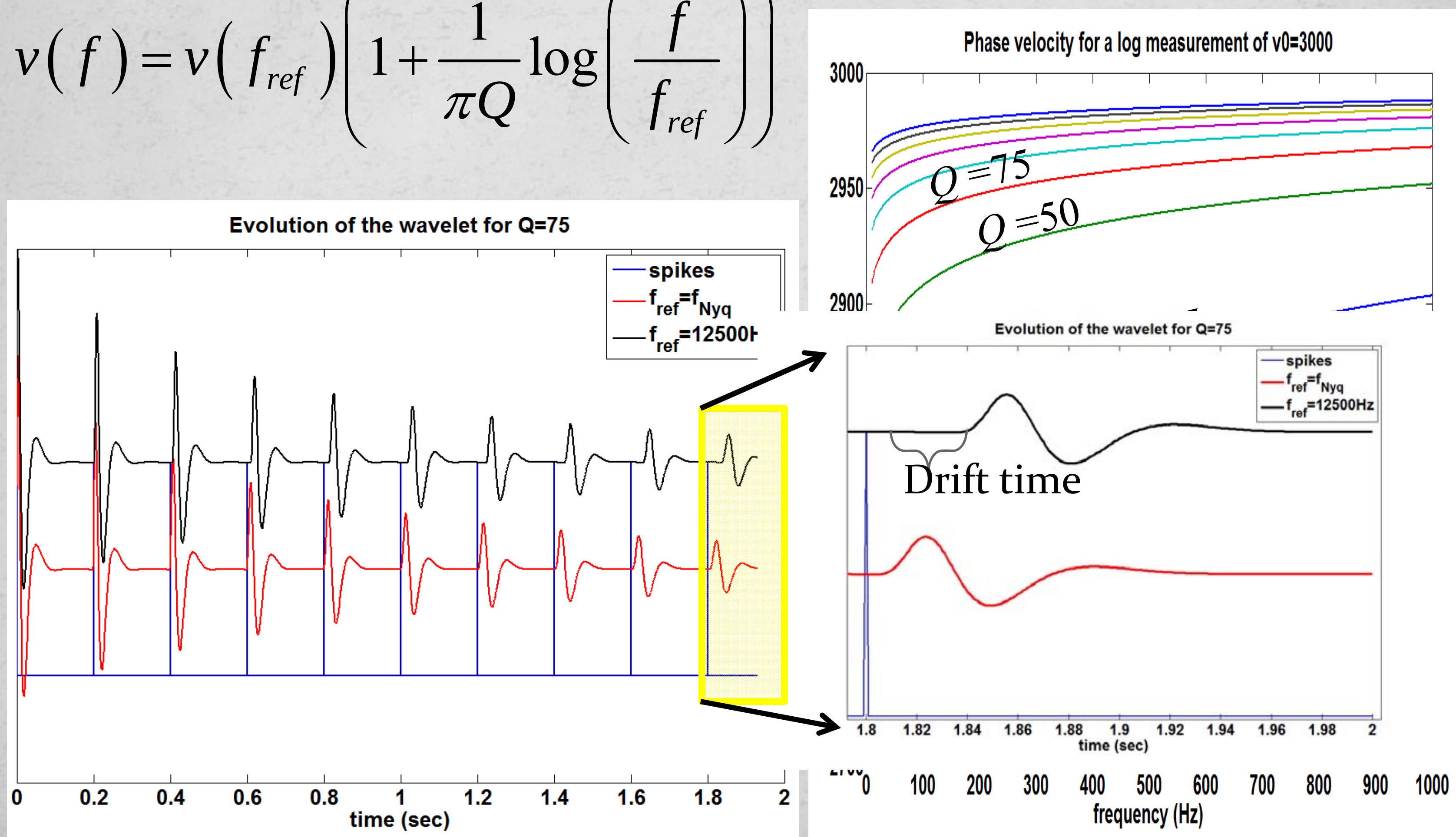




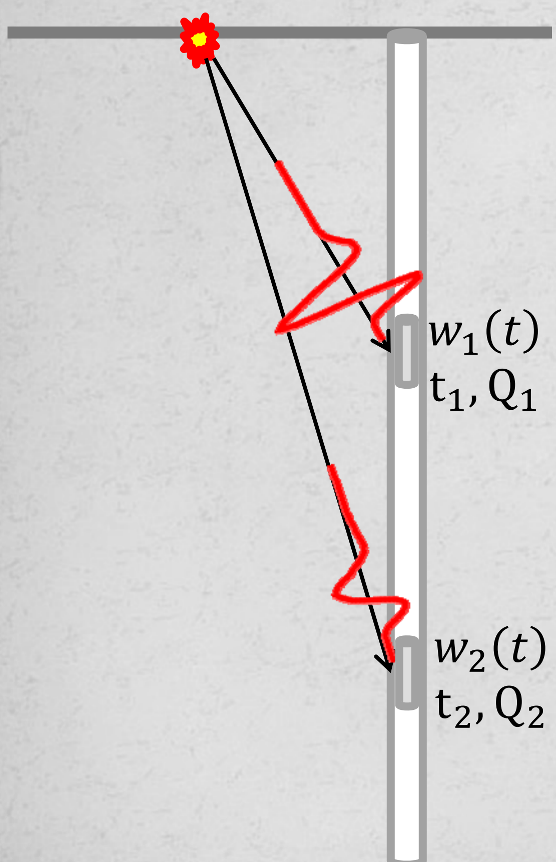
Wavelet evolution and drift

Frequency dependence of phase velocity leads to "drift"

$$v(f) = v(f_{ref})\left(1 + \frac{1}{\pi Q}\log\left(\frac{f}{f_{ref}}\right)\right)$$



Spectral Model



Amplitude spectrum of wavelet 1:

$$|\widehat{w_1}| = A_1 = T_1\ |\widehat{w_0}|e^{-\frac{\pi f t_1}{Q_1}}$$

And wavelet 2:

$$|\widehat{w_2}| = A_2 = T_2\ |\widehat{w_0}|e^{-\frac{\pi f t_2}{Q_2}}$$

Form the spectral ratio:

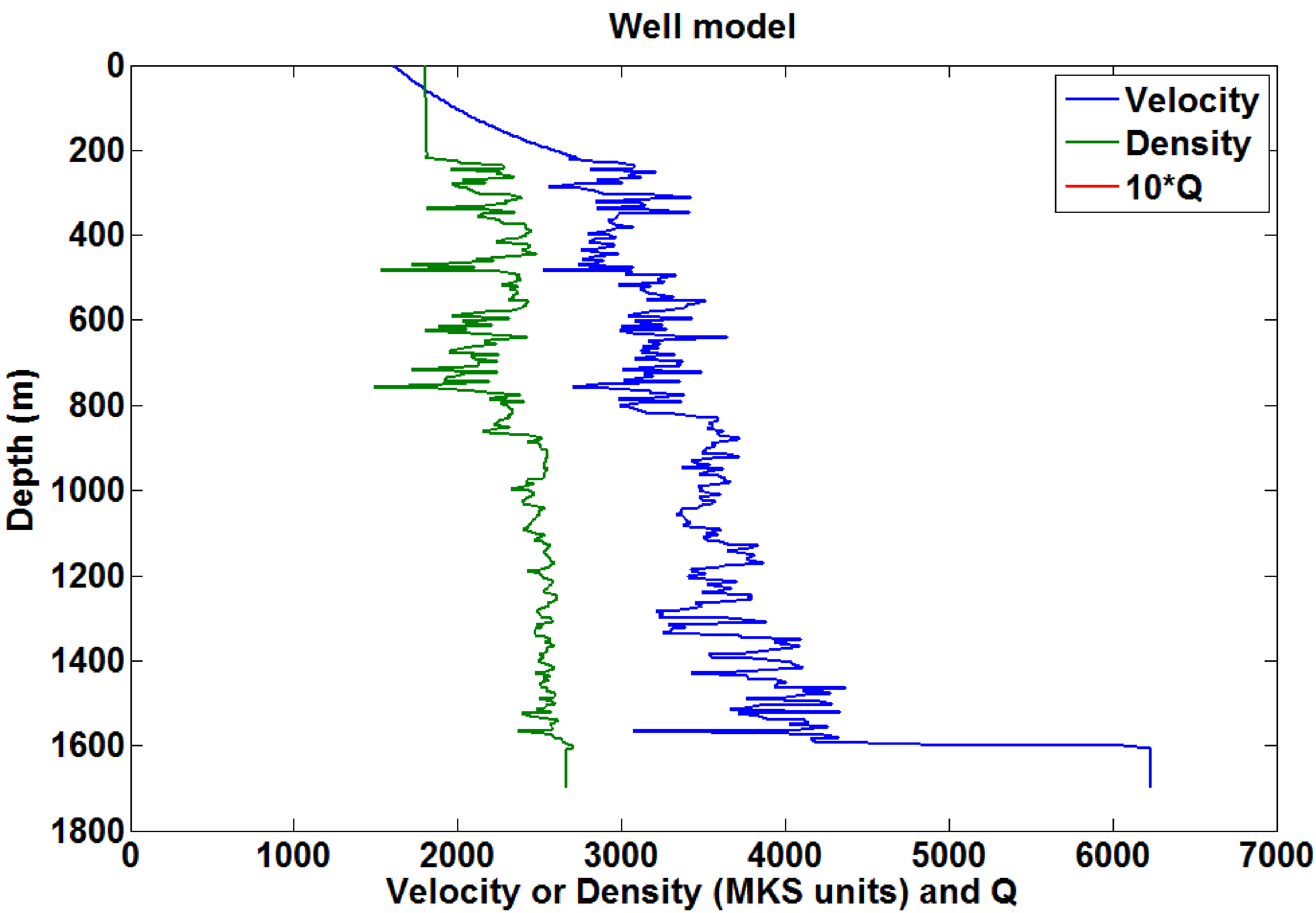
$$sr = \frac{A_2}{A_1} = \frac{T_2|\widehat{w_0}|e^{-\frac{\pi f t_2}{Q_2}}}{T_1\ |\widehat{w_0}|e^{-\frac{\pi f t_1}{Q_1}}} = \frac{T_2}{T_1}e^{-\pi f\left(\frac{t_2}{Q_2}-\frac{t_1}{Q_1}\right)}$$

Define:

$$T = \frac{T_2}{T_1} \qquad \Delta t = t_2 - t_1 \qquad Q_{int}^{-1} = \frac{1}{\Delta t}\left(\frac{t_2}{Q_2} - \frac{t_1}{Q_1}\right)$$

$$\boxed{sr = Te^{-\frac{\pi f \Delta t}{Q_{int}}}}$$

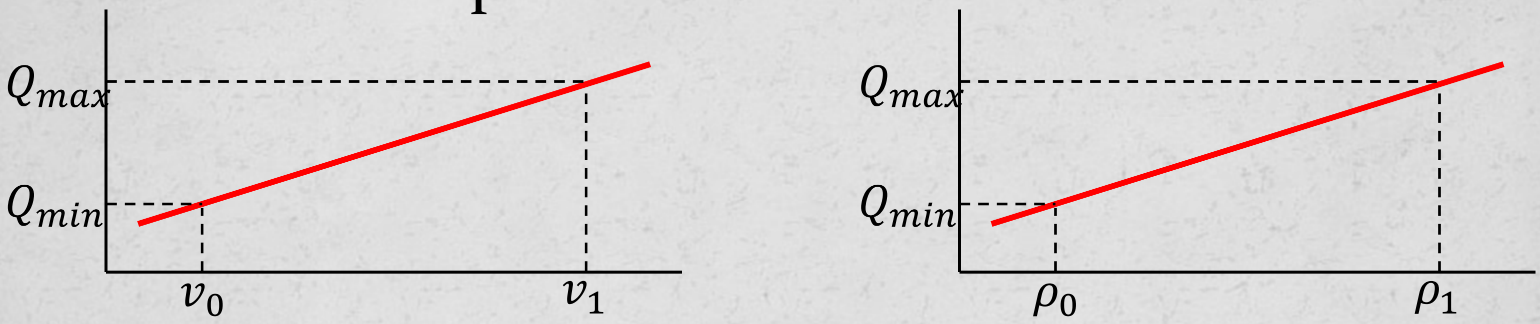
Well information



Faking Q

Assume linear relations between v_p and Q_p and between density ρ and Q_ρ

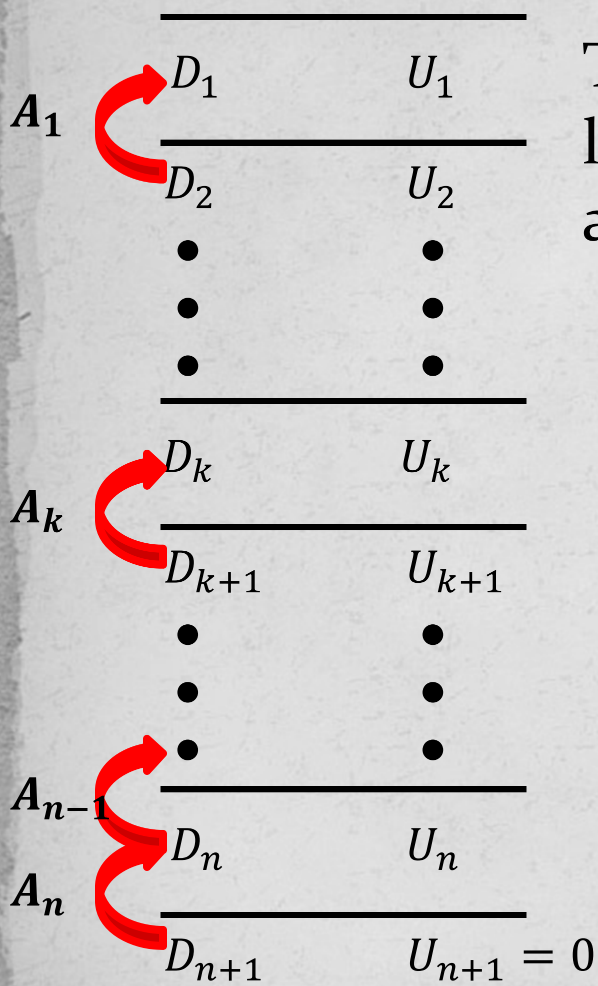
Empirical linear relations



Here v_0, v_1, ρ_0, ρ_1, and Q_{min}, Q_{max} are all prescribed empirical quantities.
Then combine the Q values from velocity and density according to

$$\frac{1}{Q} = \frac{1}{Q_p} + \frac{1}{Q_\rho}$$

The VSP problem
Connecting the top and bottom



The upgoing and downgoing fields in the top layer and the bottom half-space are related by a product of layer matrices