Towards field evidence for anelastic and dispersive AVF reflections

Chris Bird and Kris Innanen

Outline

- Review of Amplitude variations with frequency (AVF)
- Study area and objective
- Methodology
- Results
- Conclusions

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Amplitude variations with frequency

- Frequency dependent reflections in seismic field data have been associated with highly attenuative targets (Odebeatu et al. 2006)
- Geologically, this may occur for a gas saturated reservoir
- AVF inversion presents an avenue of determining subsurface rock properties/reservoir characterization

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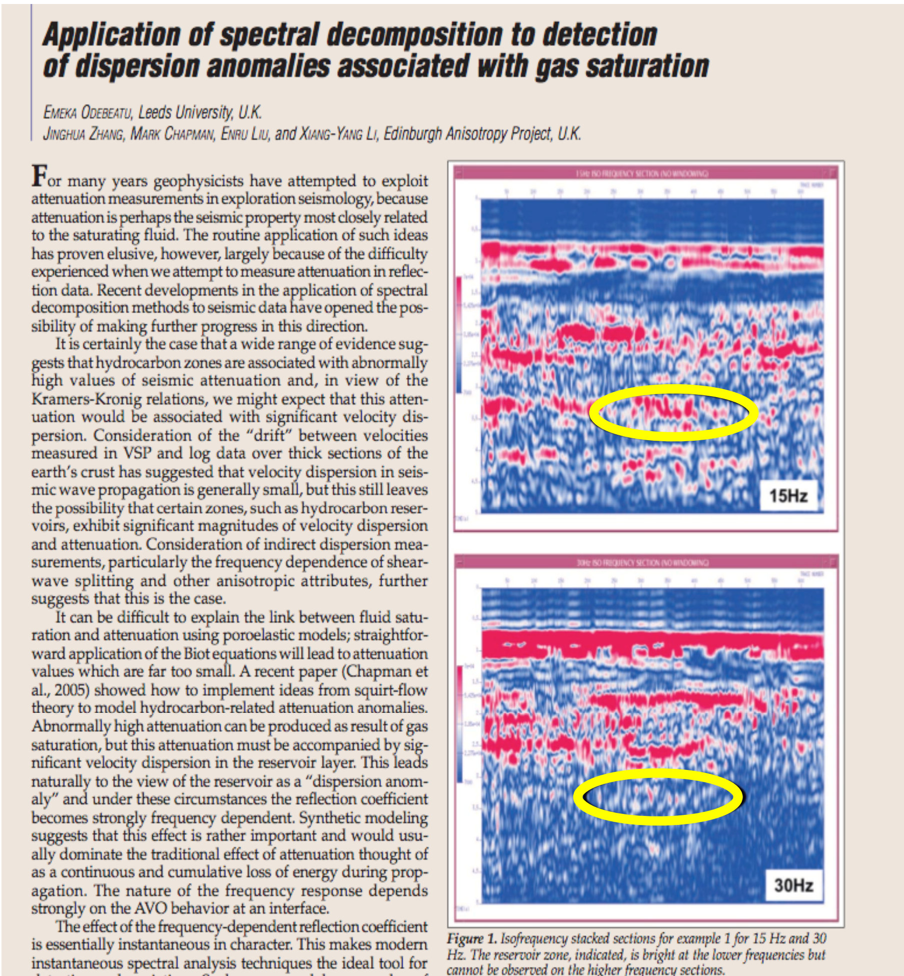
Anelastic reflectivity



Application of spectral decomposition to detection of dispersion anomalies associated with gas saturation

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For many years geophysicists have attempted to exploit attenuation measurements in exploration seismology, because attenuation is perhaps the seismic property most closely related to the saturating fluid. The routine application of such ideas has proven elusive, however, largely because of the difficulty experienced when we attempt to measure attenuation in reflection data. Recent developments in the application of spectral decomposition methods to seismic data have opened the possibility of making further progress in this direction.

It is certainly the case that a wide range of evidence suggests that hydrocarbon zones are associated with abnormally high values of seismic attenuation and, in view of the Kramers-Kronig relations, we might expect that this attenuation would be associated with significant velocity dispersion. Consideration of the "drift" between velocities measured in VSP and log data over thick sections of the earth's crust has suggested that velocity dispersion in seismic wave propagation is generally small, but this still leaves the possibility that certain zones, such as hydrocarbon reservoirs, exhibit significant magnitudes of velocity dispersion and attenuation. Consideration of indirect dispersion measurements, particularly the frequency dependence of shear-wave splitting and other anisotropic attributes, further suggests that this is the case.

It can be difficult to explain the link between fluid saturation and attenuation using poroelastic models; straightforward application of the Biot equations will lead to attenuation values which are far too small. A recent paper (Chapman et al., 2005) showed how to implement ideas from squirt-flow theory to model hydrocarbon-related attenuation anomalies. Abnormally high attenuation can be produced as result of gas saturation, but this attenuation must be accompanied by significant velocity dispersion in the reservoir layer. This leads naturally to the view of the reservoir as a "dispersion anomaly" and under these circumstances the reflection coefficient becomes strongly frequency dependent. Synthetic modeling suggests that this effect is rather important and would usually dominate the traditional effect of attenuation thought of as a continuous and cumulative loss of energy during propagation. The nature of the frequency response depends strongly on the AVO behavior at an interface.

The effect of the frequency-dependent reflection coefficient is essentially instantaneous in character. This makes modern instantaneous spectral analysis techniques the ideal tool for detecting such variations. Such an approach has a number of

Figure 1. Isofrequency stacked sections for example 1 for 15 Hz and 30 Hz. The reservoir zone, indicated, is bright at the lower frequencies but cannot be observed on the higher frequency sections.

- Frequency dependent reflection coefficient associated with a gas saturated target (Odebeatu et al. 2006)
- Our goal is to develop the means to extract target information from this type of variability

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Anelastic reflection coefficients

- Reflection Coefficient (R) in terms of vertical wavenumber

Normal incidence ⟶

$$R = \frac{k_{z_i} - k_{z_{i+1}}}{k_{z_i} + k_{z_{i+1}}} \quad (1)$$

Use nearly constant Q model from Aki and Richards (2002)

$$k = \frac{\omega}{c}\left(1 + \frac{F(\omega)}{Q}\right) \quad (2)$$

where

$$F(\omega) = \frac{i}{2} - \frac{1}{\pi}\log\left(\omega / \omega_r\right)$$

- Substitute (2) into (1) To obtain expression for anelastic Reflection coefficients.

$$R(\omega) = \frac{\frac{1}{c_i}\left(1 + \frac{F(\omega)}{Q_i}\right) - \frac{1}{c_{i+1}}\left(1 + \frac{F(\omega)}{Q_{i+1}}\right)}{\frac{1}{c_i}\left(1 + \frac{F(\omega)}{Q_i}\right) - \frac{1}{c_{i+1}}\left(1 + \frac{F(\omega)}{Q_{i+1}}\right)} \quad (3)$$

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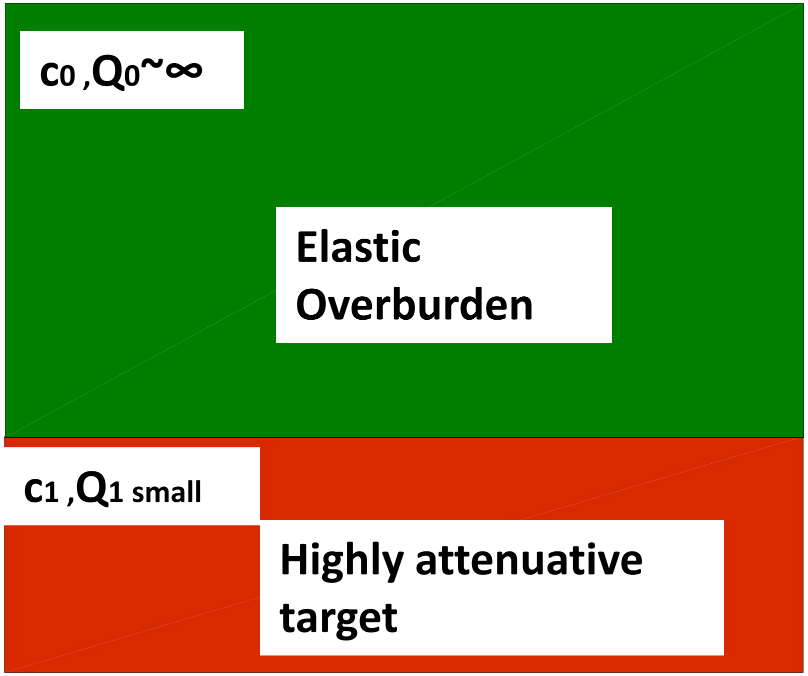
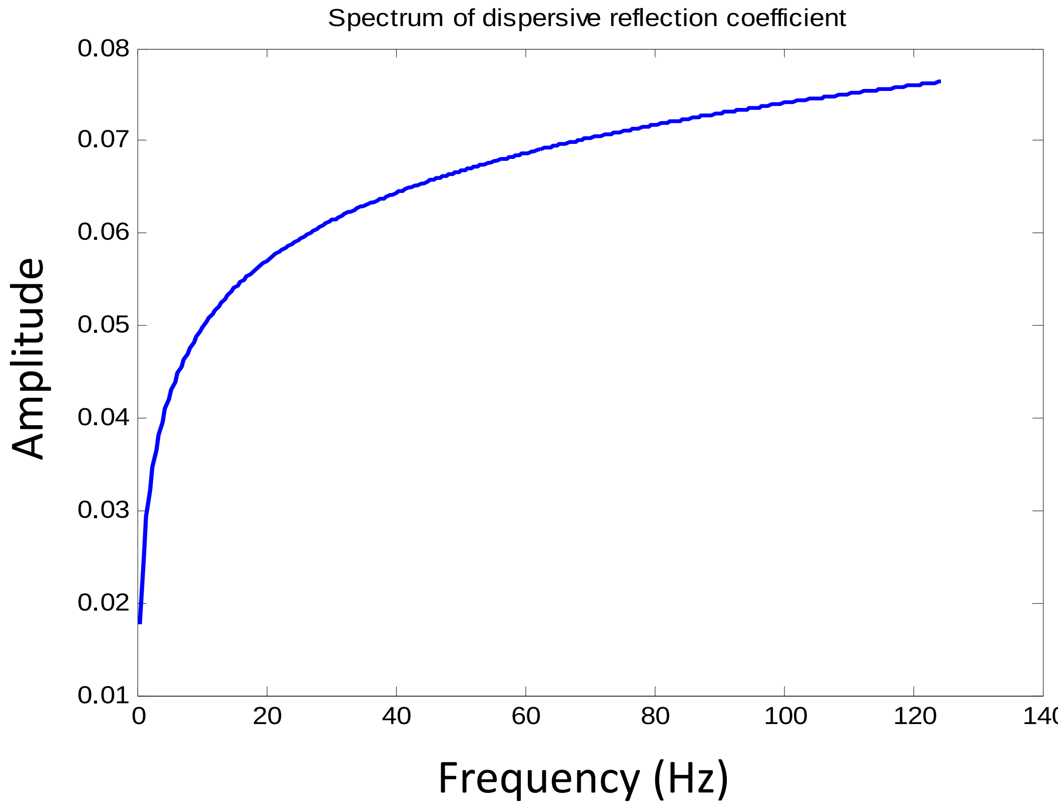
Anelastic reflection coefficients





- Equation (3) becomes

$$R(\omega) = \frac{\frac{1}{c_i} - \frac{1}{c_{i+1}}\left(1 + \frac{F(\omega)}{Q_{i+1}}\right)}{\frac{1}{c_i} - \frac{1}{c_{i+1}}\left(1 + \frac{F(\omega)}{Q_{i+1}}\right)} \qquad (4)$$

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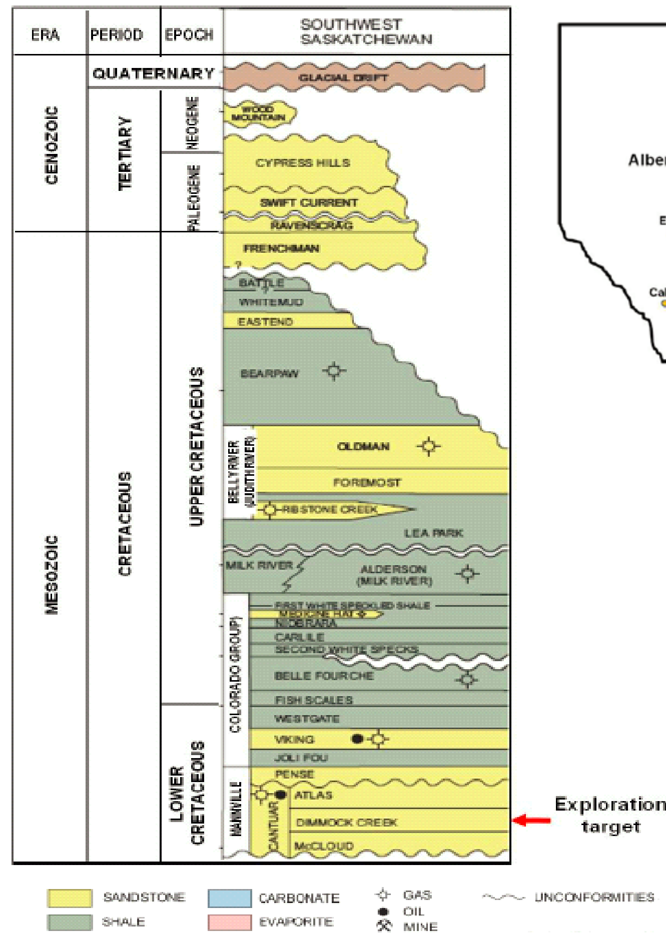
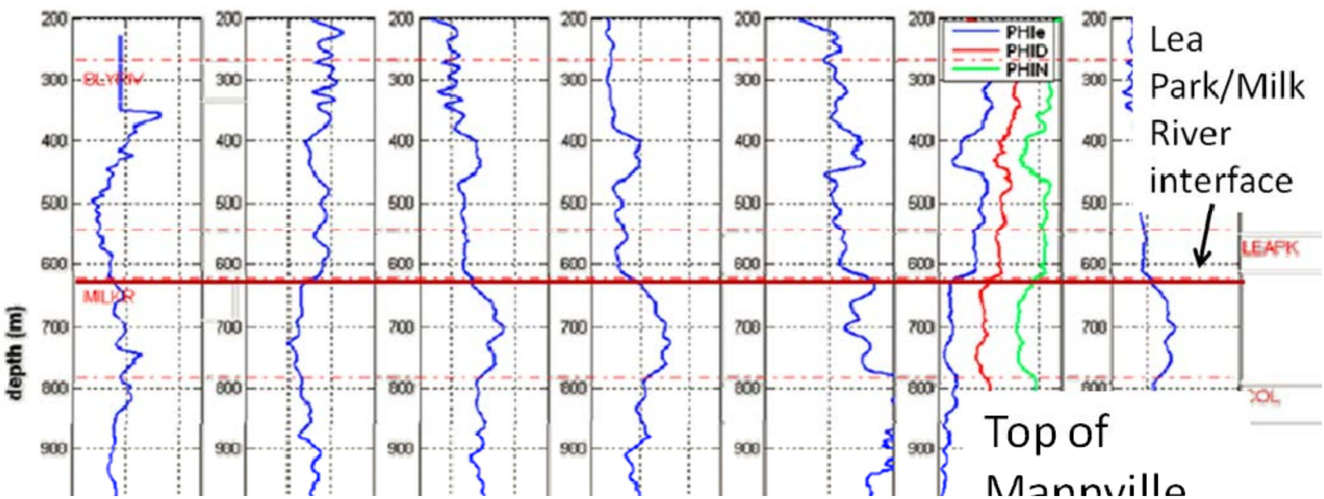
Study area, data and objective

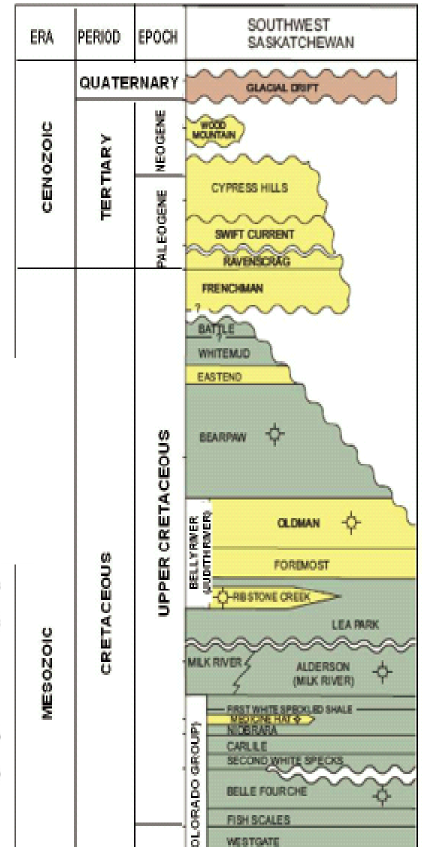
- Ross Lake heavy oil field is located in South West Saskatchewan
- Owned and operated by Husky Energy
- The reservoir is a channel sand, of Cretaceous age, in the Cantaur Formation of the Mannville group (Zhang, 2010)
- A number of VSP surveys performed including a zero-offset VSP



From Saskatchewan Industry and Resources, 2006

Study area, data and objective





Objective: extract the reflection coefficient from the Mannville and analyse for AVF signature, then compare with a control reflection from the Lea Park/Milk River interface

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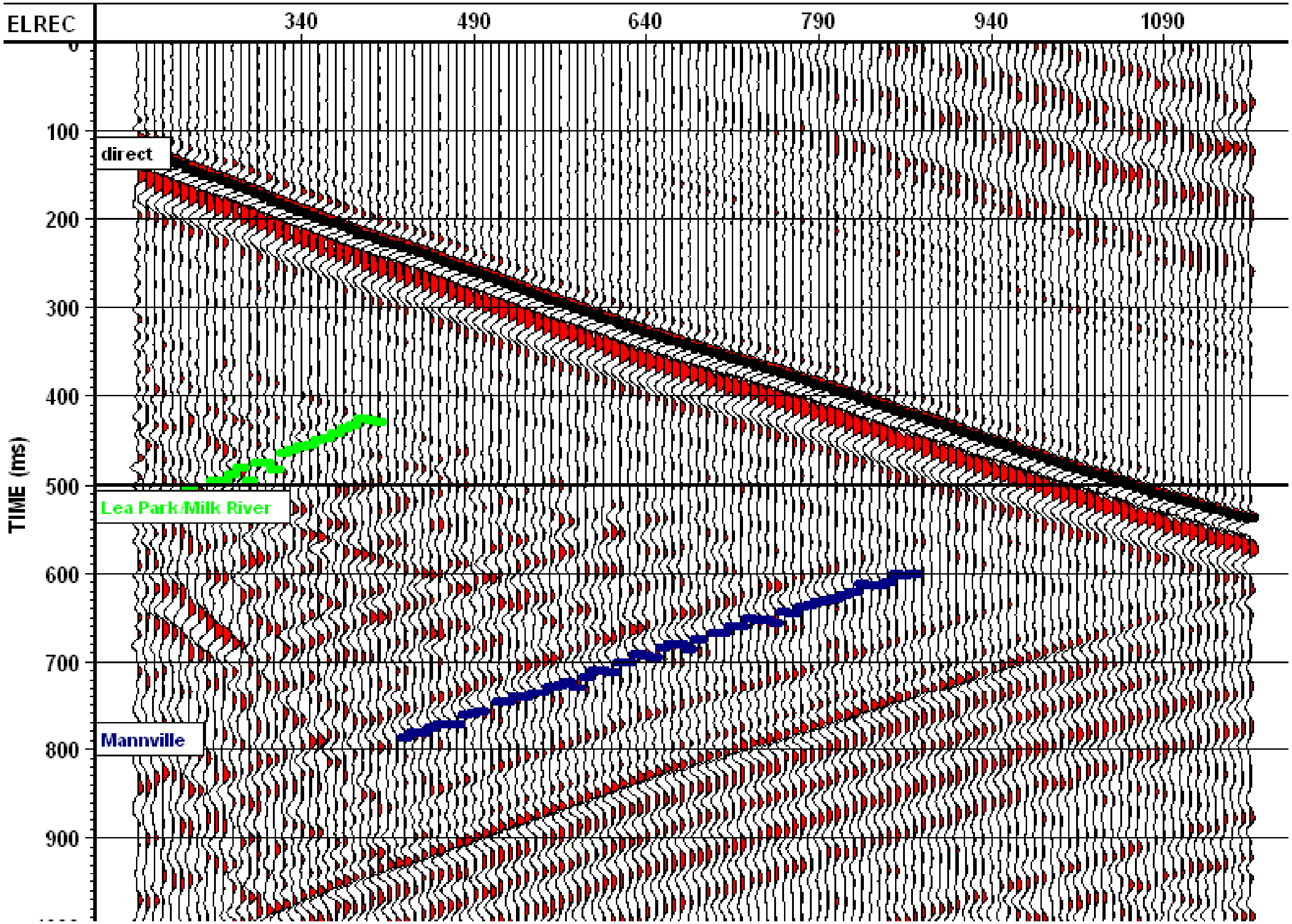
From Zhang, (2010)

Zero-offset vertical component VSP



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Methodology

Lira's Method – elastic case

$$P_n = \left(e^{ik_0(z_1-z_0)}T_{01}\cdots e^{ik_{n-1}(2z_n-z_{n-1}-z)}\right)R_n$$

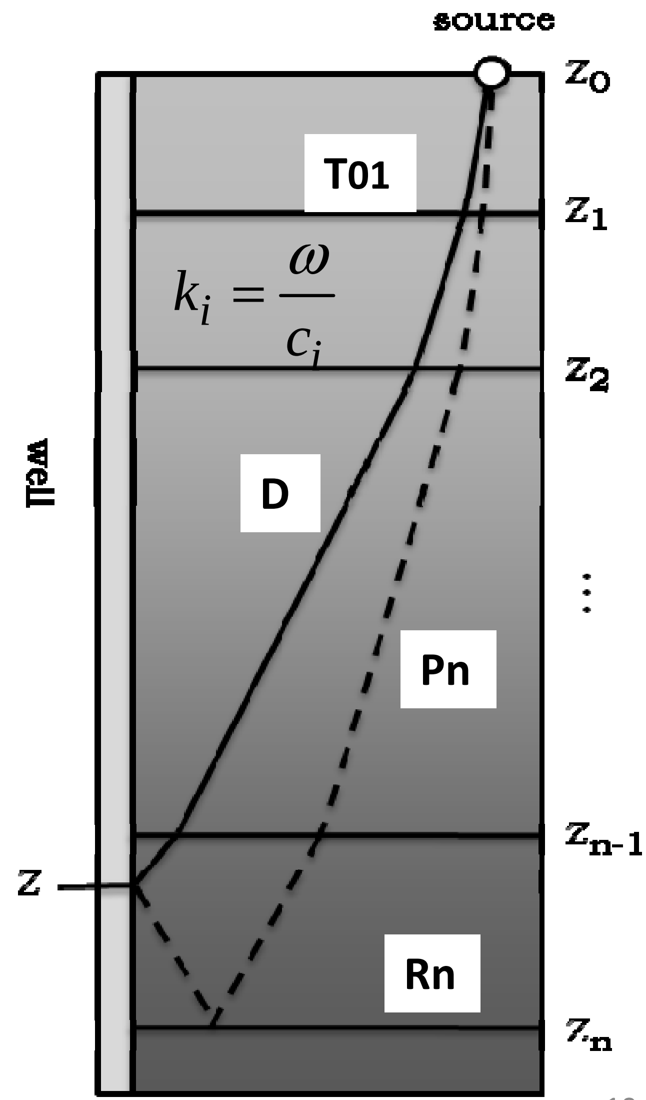
$$\left|P_n\right| = \left[T_{01}T_{12}\cdots T_{(n-2)(n-1)}\right]R_n$$

$$D = \left(e^{ik_0(z_1-z_0)}T_{01}\cdots e^{ik_{n-1}(z-z_{n-1})}\right)$$

$$\left|D\right| = \left[T_{01}T_{12}\cdots T_{(n-2)(n-1)}\right]$$

$$P_{cor} = \frac{\left|P_n\right|}{\left|D\right|} \approx R_n$$

For small Zn-Z



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Methodology anelastic case

$$k_i = \frac{\omega}{c_i}\left(1 + \frac{F(\omega)}{Q_i}\right) \qquad F(\omega) = \frac{i}{2} - \frac{1}{\pi}\log\left(\omega/\omega_r\right)$$

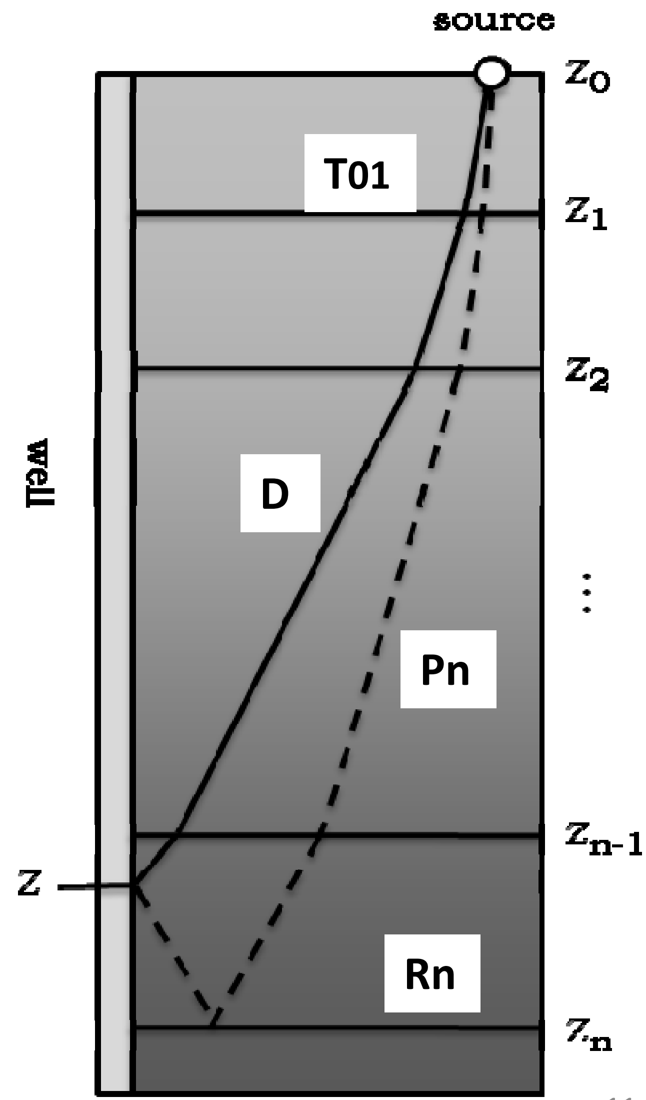
Plugging back into the expressions for Pn and D we obtain

$$P_{cor} = \frac{|P_n|}{|D|} = R_n \times e^{\frac{-\omega(z_n - z)}{c_{n-1}Q_{n-1}}}$$

We see that for small Zn-Z we have

$$P_{cor} \to R_n$$

Lira, J. E., Weglein, A. B., Bird, C. W. and Innanen, K. A., 2011, Determination of reflection coefficients by comparison of direct and reflected VSP events: CREWES Annual Report, **23,** 1-13.



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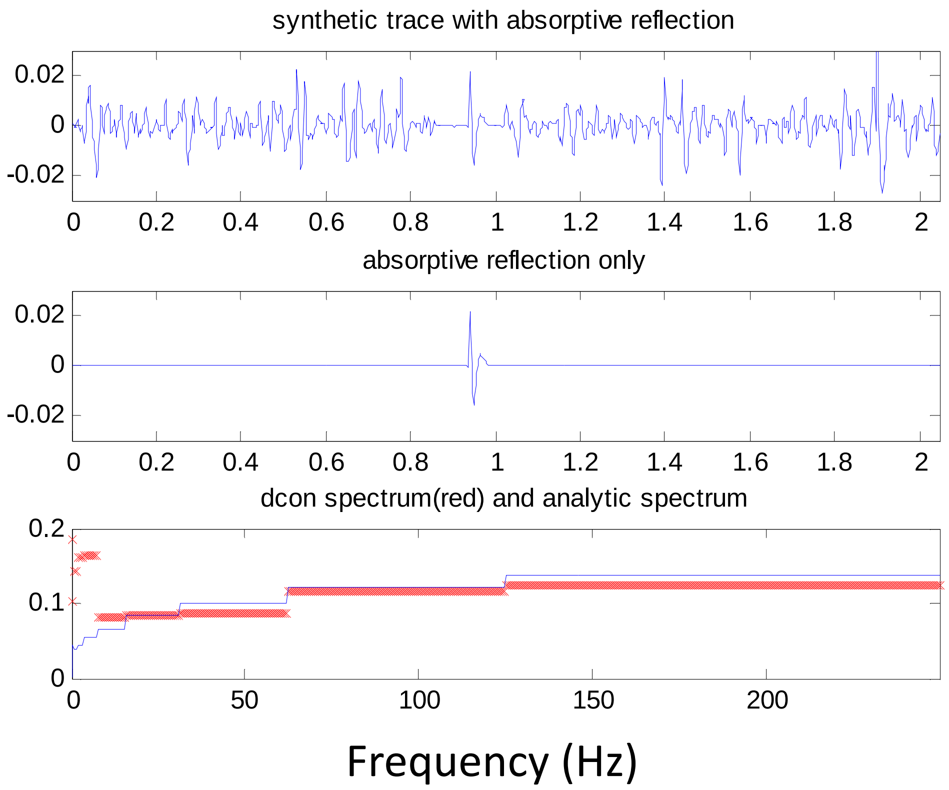
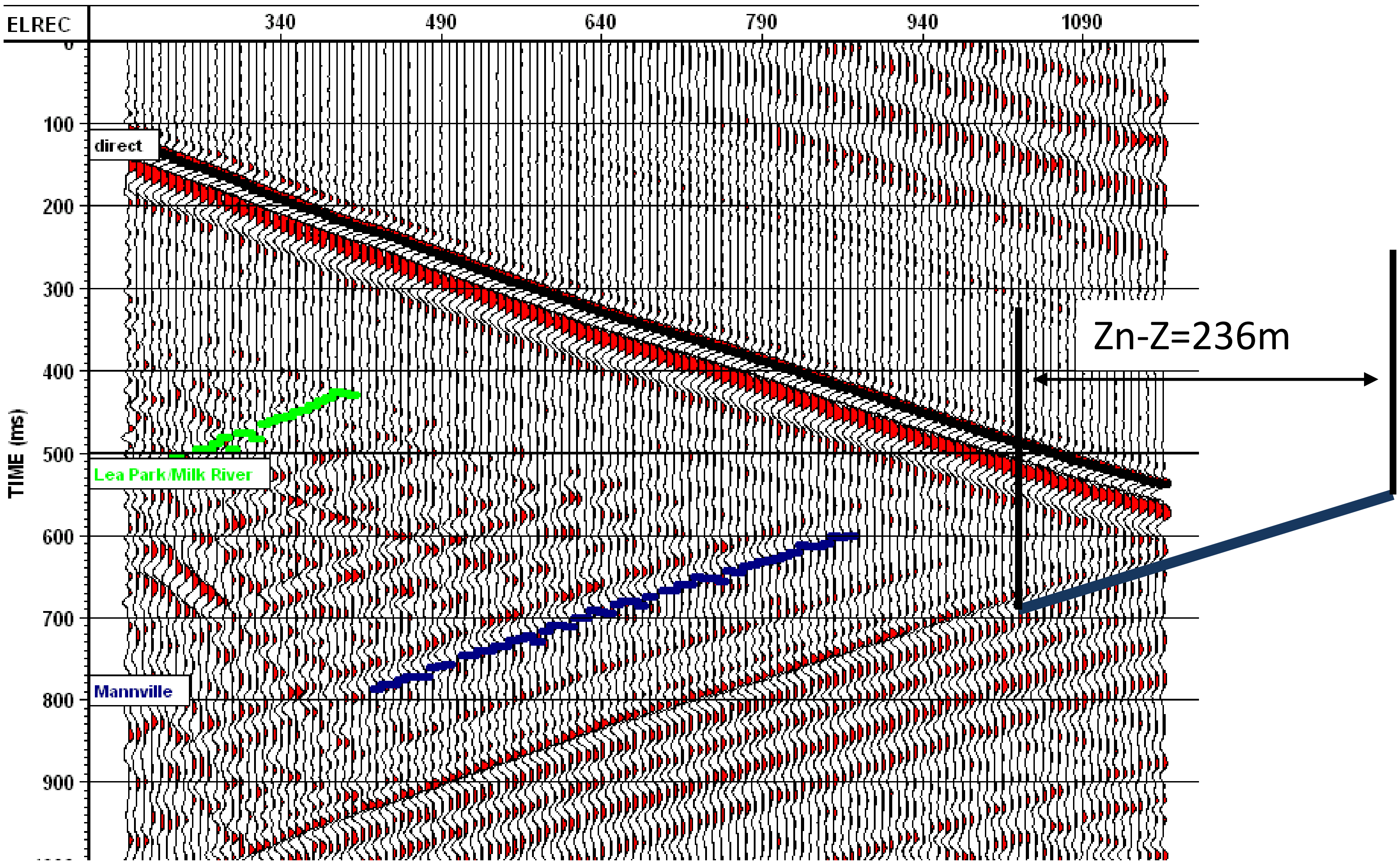
Extraction of spectra

Fast S-transform

- We have a calibrated, fast S-transform (Brown et al., 2010) which testing indicates offers high fidelity estimates of the local spectra of seismic events



Extraction of spectra



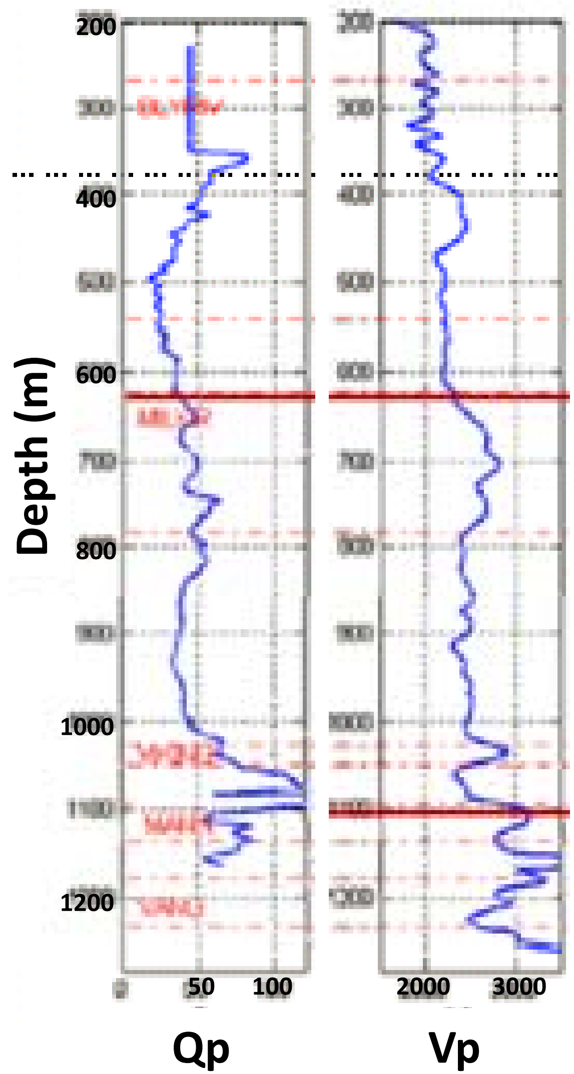
Q compensation

- In order to use Lira's method recall that

$$P_{cor} = \frac{|P_n|}{|D|} = R_n \times e^{\frac{-\omega(z_n - z)}{c_{ave} Q_{ave}}}$$

- Since Zn-Z is not small so division of primary by direct will not yeld R. However, using average values of velocity and Q we can calculate R

$$R_n = \frac{|P_n|}{|D|} \times e^{\frac{\omega(z_n - z)}{c_{ave} Q_{ave}}}$$



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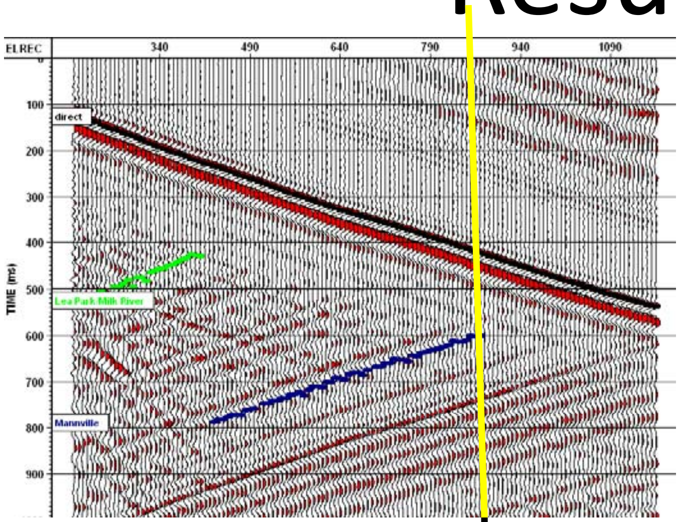
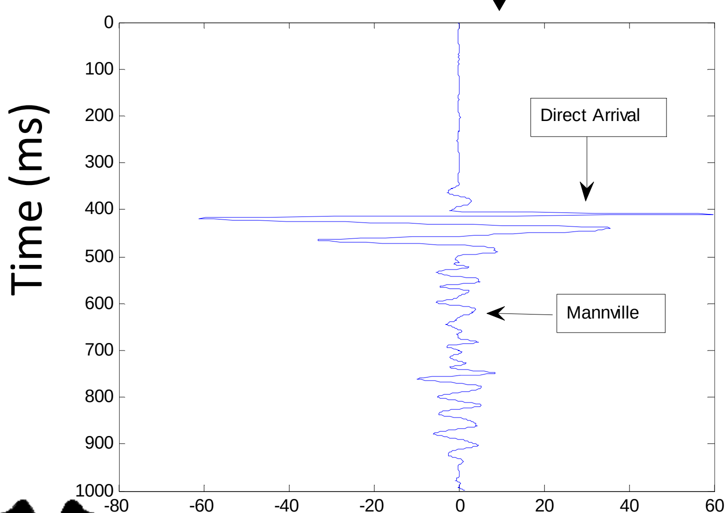
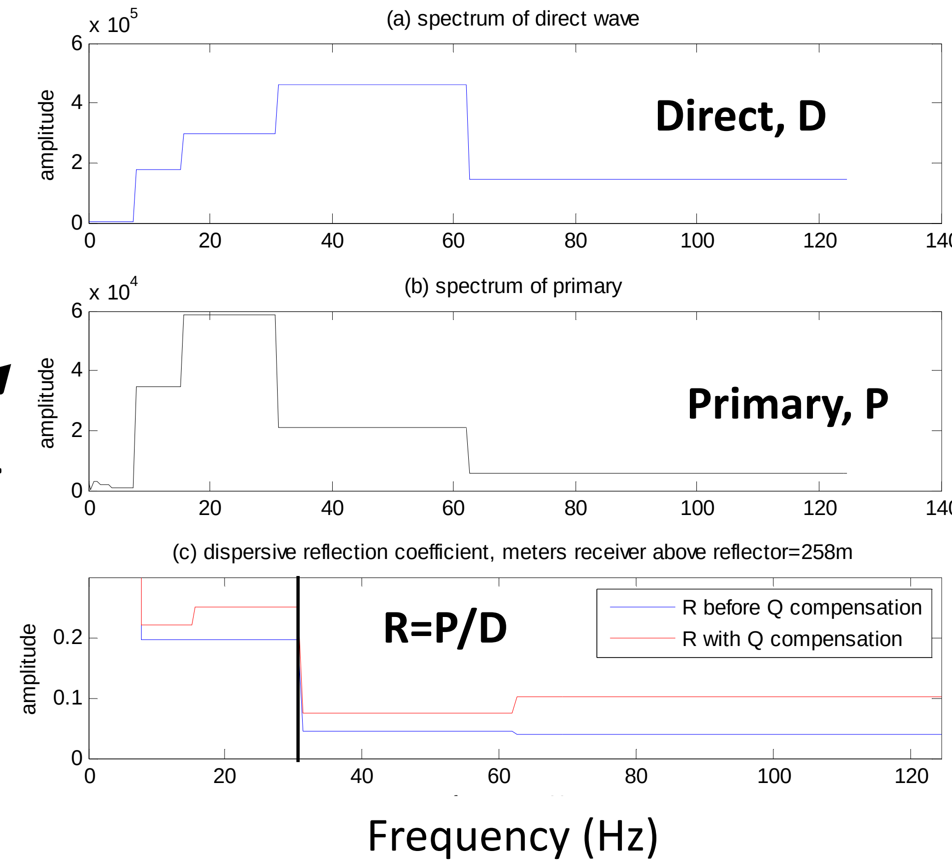
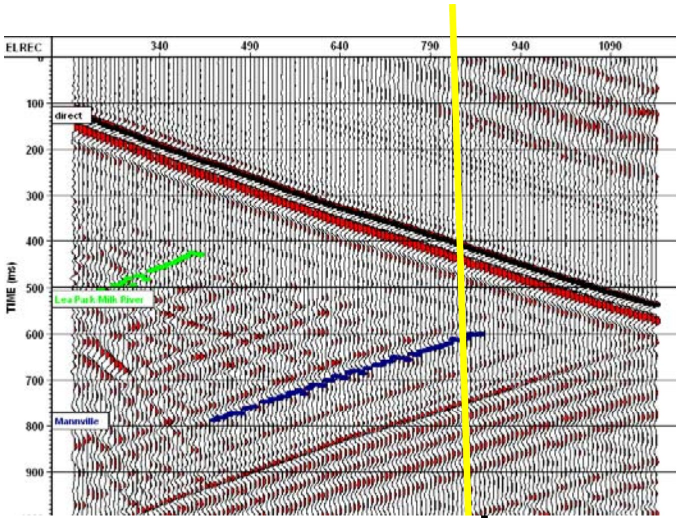
Results-Mannville

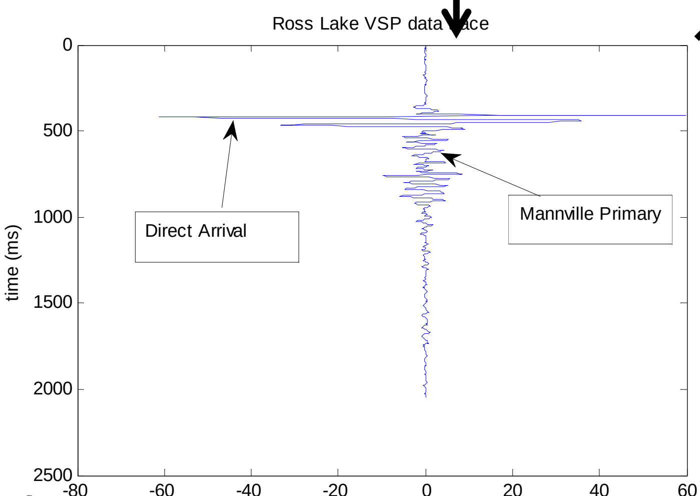




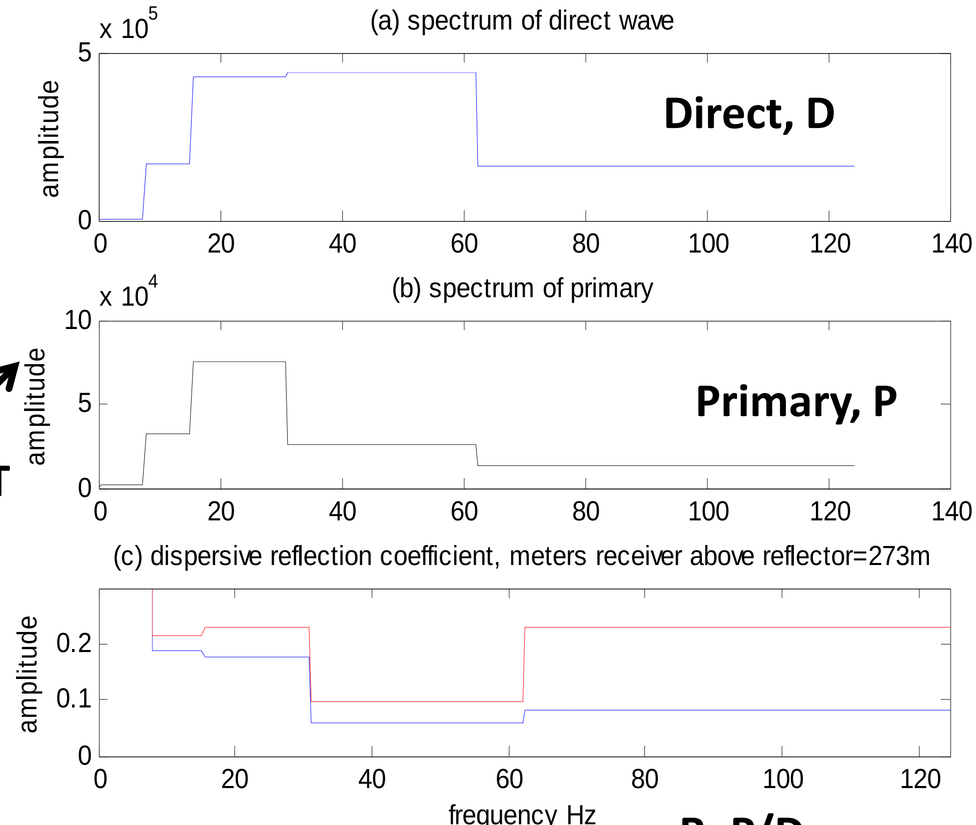
FST



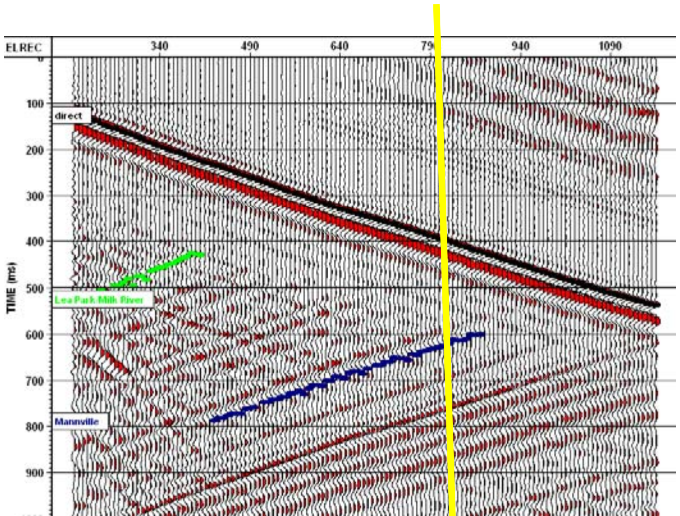

ELREC
340
490
640
790
940
1090
TIME (ms)
100
200
300
400
500
600
700
800
900
direct
Lea Park Milk River
Mannville


Ross Lake VSP data trace
time (ms)
0
500
1000
1500
2000
2500
-80
-60
-40
-20
0
20
40
60
Direct Arrival
Mannville Primary

FST


(a) spectrum of direct wave
x 10^5
amplitude
Direct, D
(b) spectrum of primary
x 10^4
amplitude
Primary, P
(c) dispersive reflection coefficient, meters receiver above reflector=273m
amplitude
frequency Hz

R=P/D


ELREC
340
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TIME (ms)
100
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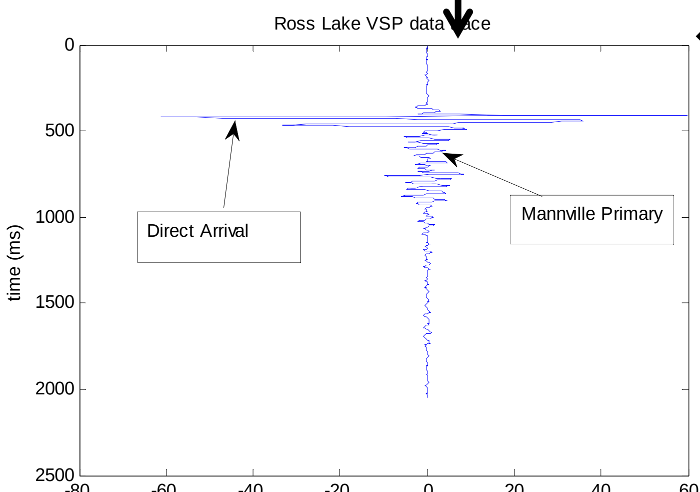
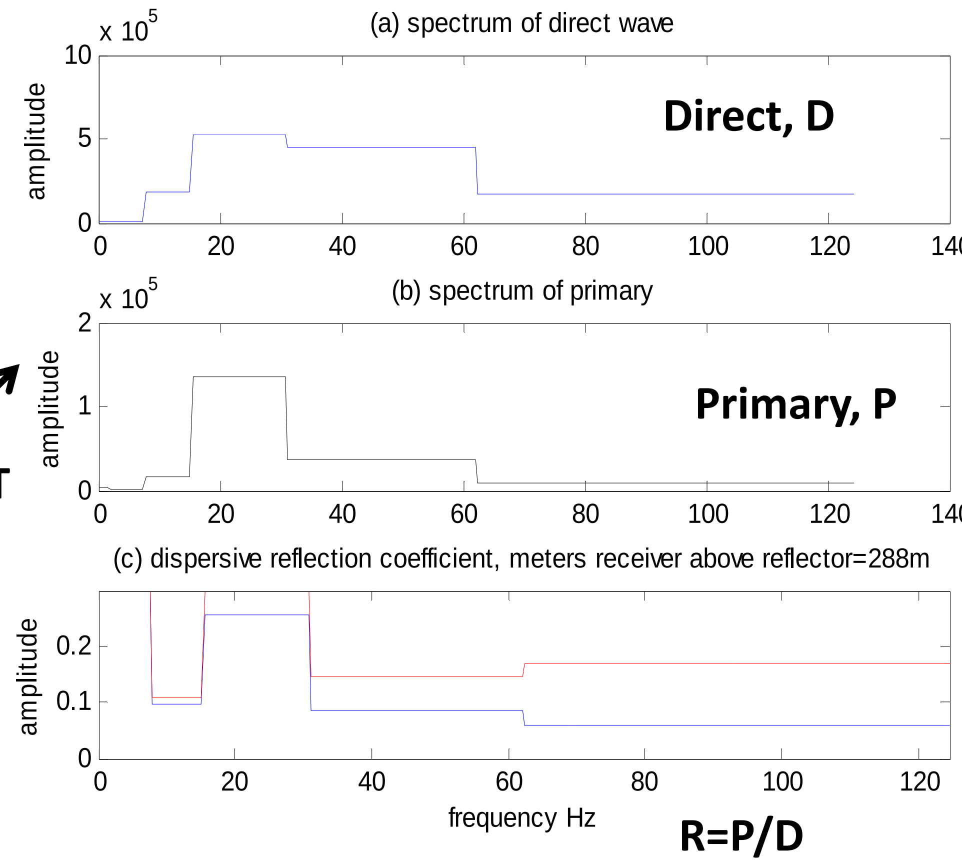
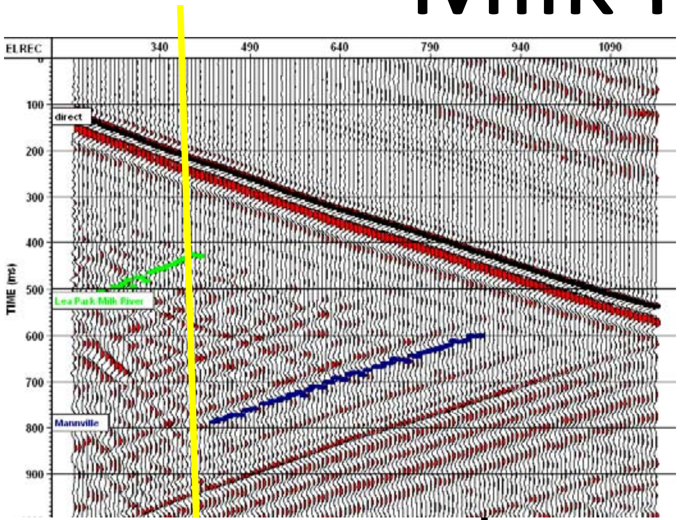
direct
Lea Park Milk River
Mannville

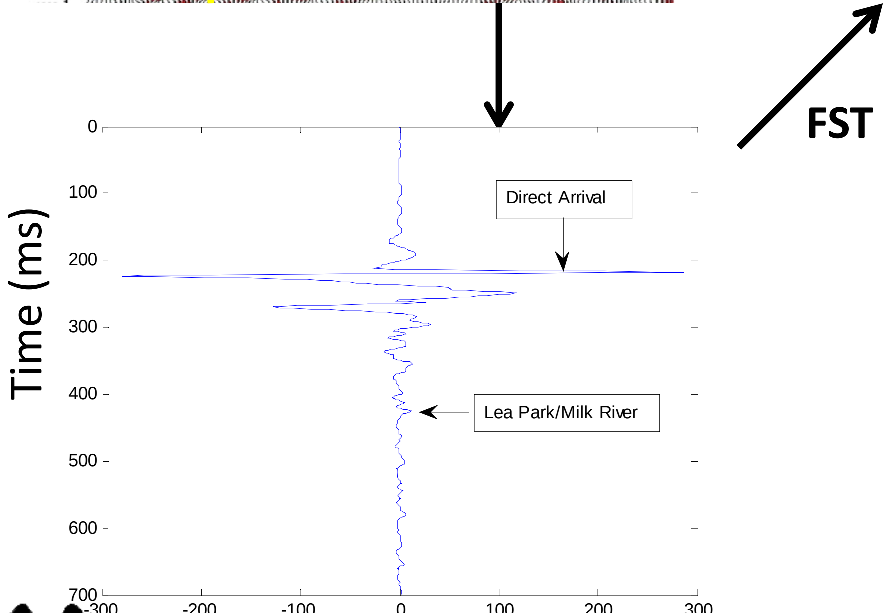

Ross Lake VSP data trace
time (ms)
0
500
1000
1500
2000
2500
-80
-60
-40
-20
0
20
40
60
Direct Arrival
Mannville Primary

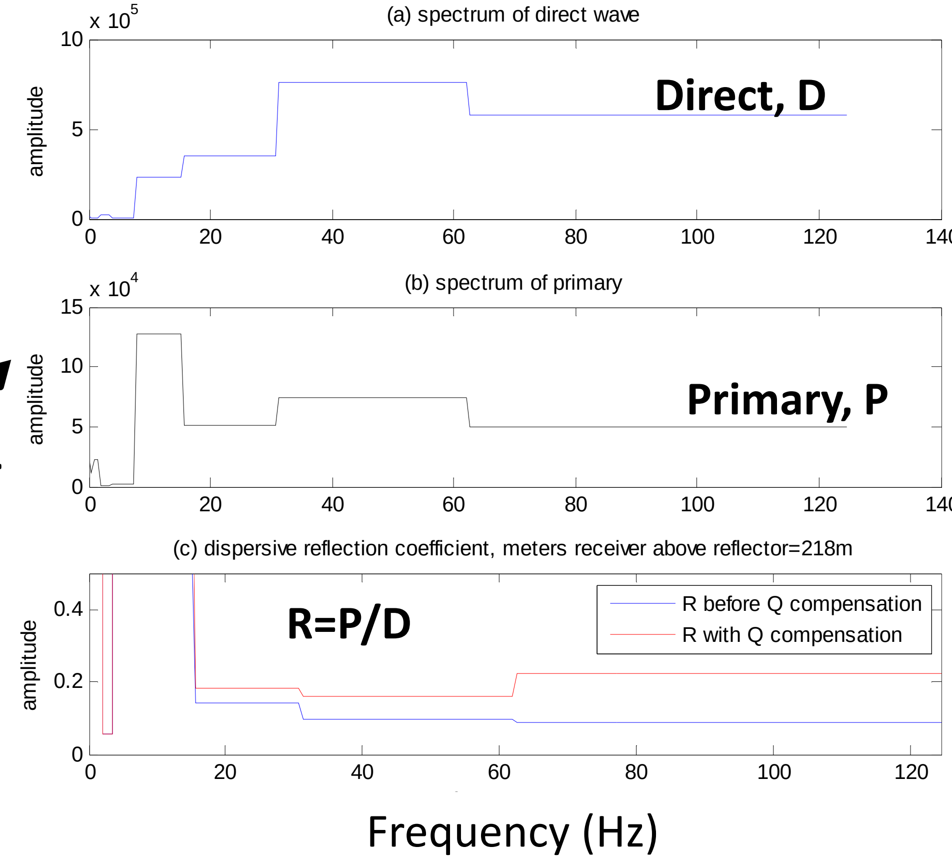
FST


(a) spectrum of direct wave
x 10^5
amplitude
Direct, D
(b) spectrum of primary
x 10^5
amplitude
Primary, P
(c) dispersive reflection coefficient, meters receiver above reflector=288m
amplitude
frequency Hz
R=P/D

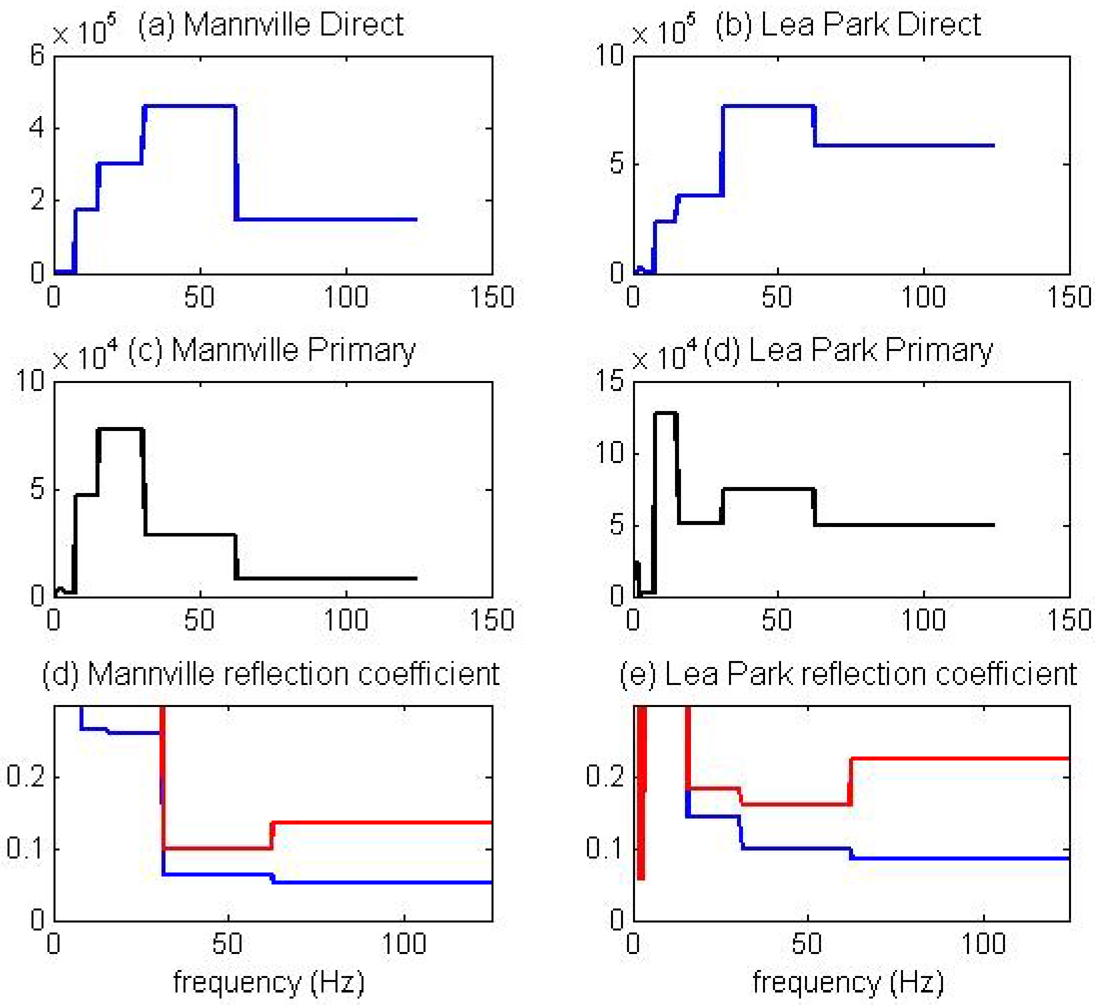
Milk River/Lea Park

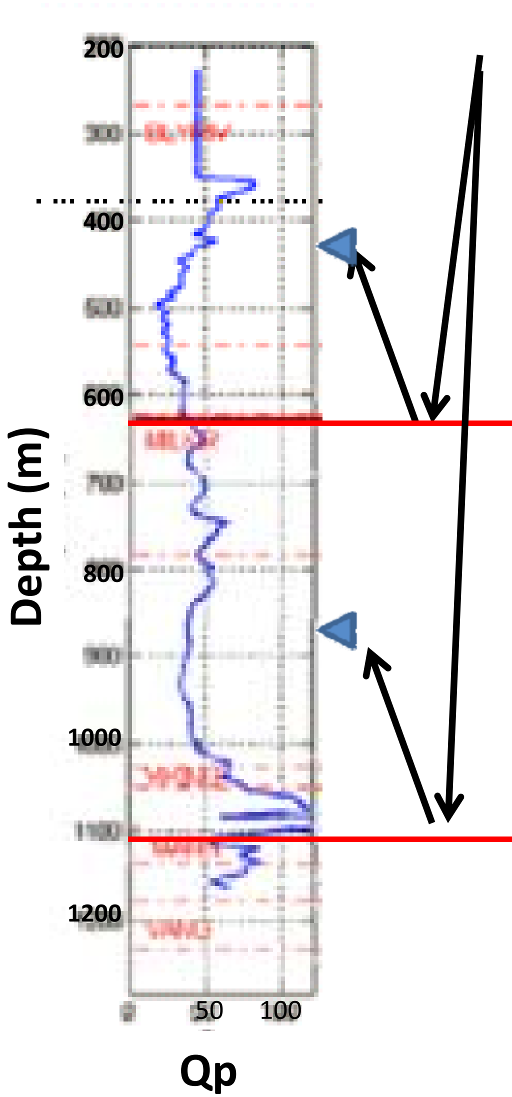






Results





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Conclusions

- We applied a method developed by Lira et al., (2011) for estimating the frequency dependent reflection coefficient by comparing the direct and reflected VSP events
- The method was applied to an absorptive reflection in the Mannville and analyzed for an AVF signature
- As a control, the method was applied to a reflection (Lea Park/Milk River) not associated with a contrast in Q

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Conclusions

- It was found that the control reflection coefficient had an AVF signature as well
- This VSP example is not providing a good control. Therefore it is hard to know if the apparent AVF signature in the Mannville is real

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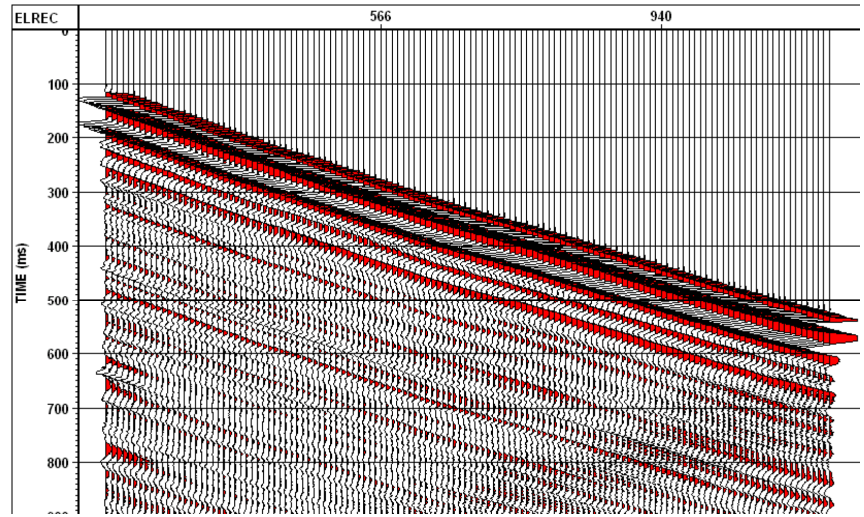
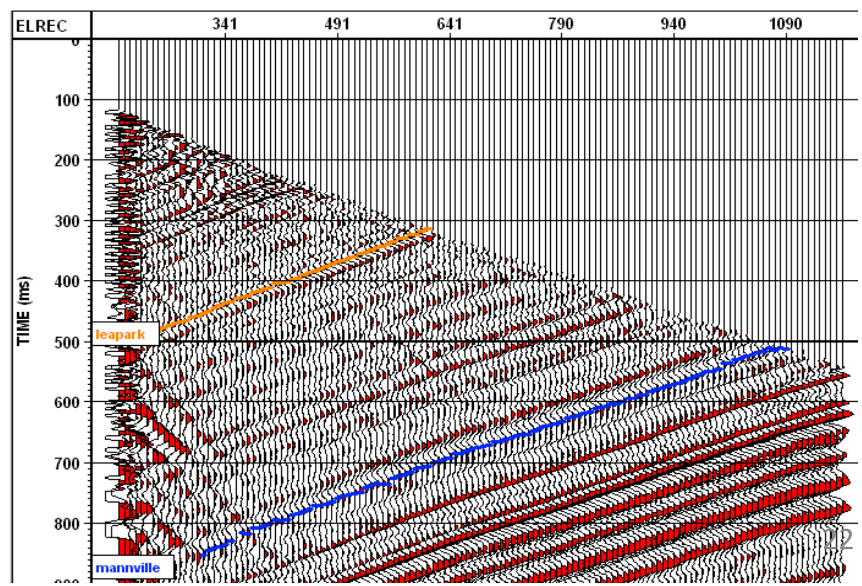
Future Work

- Look for a better control and target reflectors
- Study the potential for wavefield separation techniques which do not dominate the spectra of our events
- Merge with existing AVF inversion methods of Bird thesis research





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Questions?

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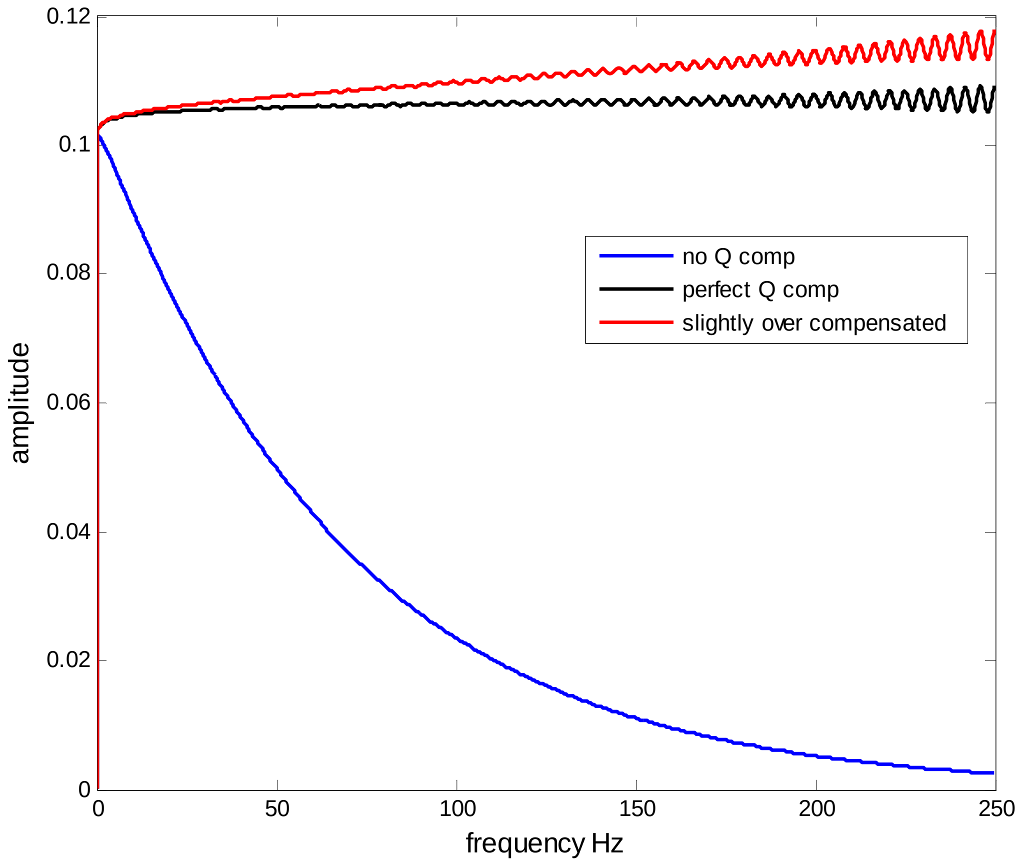
0.12
0.1
0.08
0.06
0.04
0.02
0
amplitude
0
50
100
150
200
250
frequency Hz
no Q comp
perfect Q comp
slightly over compensated