Comparison of Wavelet Estimates from VSP and Surface Data

Linping Dong*, Gary F. Margrave and Kevin W. Hall
CREWES, 2500 University Dr., N.W., Calgary, AB, T2N 1N4
dongl@ucalgary.ca

ABSTRACT

Summary

The accuracy of wavelets estimated by deconvolution of surface seismic data can be verified by several approaches. Traditionally, the results of deconvolution are compared to synthetic seismograms generated from sonic logs. If these results are consistent in time and amplitude, the wavelet estimates are considered to be accurate. In most cases this comparison is difficult, because the software used to generate synthetics typically convolves the reflection coefficients with a stationary wavelet, while the real wavelet is nonstationary.

Here, we compare the wavelets obtained from VSP downgoing waves with wavelets estimated from surface data by multi-window Wiener deconvolution, frequency domain spiking deconvolution, and Gabor deconvolution (Margrave and Lamoureux, 2001). Since these wavelets experience different degrees of attenuation, a Q-filter is designed and applied to the wavelets obtained from VSP data to make them comparable to wavelets estimated from surface data, in both time and frequency domains. A normalized cross-correlation method is used to obtain a numerical measure of wavelet similarity. Our results are consistent with the hypothesis that Gabor deconvolution can accurately estimate nonstationary wavelets embedded in real seismic data. The results also suggest wavelets estimated by Gabor deconvolution are superior to those obtained from multi-window Wiener or frequency-domain spiking deconvolutions.

Introduction

A simultaneous VSP and 2D surface seismic survey was provided by EnCana (formerly PanCanadian) for this research. The recording geometry is shown in *Fig. 1*. Receivers were positioned between 322 and 1820 m depth at a receiver interval of 20 m for a total of 75 receiver locations within the borehole. An additional 78 geophones were placed between 30 and 2310 m from the borehole at a 30 m interval on the surface. Five source points were used for this survey, located 27, 430, 960, 1350 and 1700 m from the borehole. A 12 s, 10-96 Hz non-linear sweep was used to record 16 second uncorrelated shot records at a 2 ms sample rate. *Fig. 2* shows the zero-offset vertical component VSP record after vertical summation. *Fig. 3* shows an example of the data recorded at the surface. Both shot gathers and VSP sections are used for wavelet estimation.

The wavelet comparison is based on the propagating wavelet model proposed by Margrave and Lamoureux (2001). Suppose the effect of geometric spreading on the wavelets has been removed. The propagating wavelet can now be modeled as an attenuated source signature which can be expressed as

$$\omega_p(t,f) = \omega(f)\alpha_Q(t,f), \qquad (1)$$

where $\omega_p(t,f)$ denotes the Fourier spectrum of propagating wavelet as a function of time, $\omega(f)$ is the spectrum of the stationary source signature, and $\alpha_Q(t,f)$ describes the time-frequency effects of attenuation. In our case, the surface and VSP data share the same source. Assuming a constant-Q model, the attenuation term $\alpha_Q(t,f)$ can be written as

$$\alpha_Q(t,f) = e^{-\frac{\pi f t}{Q} + iH\left(\frac{\pi f t}{Q}\right)}, \qquad (2)$$

where H denotes the Hilbert transform, and Q is the non-frequency dependent quality factor (Aki and Richards, 1980). Equation 2 shows the attenuation surface is equivalent to a minimum-phase, time-variant low-pass filter.

Propagating Wavelet Estimation

Downgoing waves recorded on VSPs represent a direct observation of the propagating wavelet. Major steps in VSP wavelet estimation are: 1) vertical sum, 2) geometric spreading correction, 3) downgoing wave flattening, and 4) f-k filter. The purpose of the vertical sum is to improve the S/N ratio. The geometric spreading correction removes nonstationarity relating to wavefront divergence, which is independent of frequency. The velocity function used in the geometric spreading correction should be the same as that used for surface seismic processing (next section). After flattening downgoing waves, a f-k filter is applied to separate downgoing waves from the full wavefield.

Three methods were used to estimate the propagating wavelet from surface data; Weiner deconvolution, frequency-domain spiking deconvolution, and Gabor deconvolution. In Wiener deconvolution, the inverse operator is obtained with the Wiener-Levinson algorithm. The wavelet is actually a minimum-phase match filter, for matching the inverse operator to an impulse. In frequency-domain spiking deconvolution, the amplitude spectrum of windowed data is smoothed and stabilized to get the amplitude spectrum of the wavelet, followed by a Hilbert transform to calculate the phase spectrum. Finally, the wavelet is reconstructed by inverse Fourier transforming the estimated spectra. To estimate wavelets with Gabor deconvolution, we apply the Gabor transform using Gaussian windows with 80 percent window overlap, then smooth the Gabor magnitude spectrum along hyperbolae ($tf = \text{constant}$) to estimate the magnitude of the attenuation function. The source signature can now be estimated by dividing the Gabor magnitude spectrum by the attenuation estimate and averaging over time. A

Hilbert transform over frequency at constant time, applied to the logarithm of the product of the attenuation surface and the source signature provides the associated minimum phase estimate. Parameters such as window length, stabilization factor, operator length, and frequency smoothing length were the same for all three methods.

It is important to choose a wavelet at the correct traveltime on surface data to compare to the wavelet measured at a specific traveltime on the VSP data. The relationship between the one-way traveltime to a receiver in the borehole for an offset VSP (t_1), and the two-way traveltime of a reflection recorded at the surface from a reflector at the same depth (t_2), can be expressed as

$$t_2 = \sqrt{\frac{x^2}{v_{stk}^2} + 4\left(\frac{t_1^2 v_a^2 - c^2}{v_{stk}^2}\right)}, \qquad (3)$$

where v_a is the average velocity at time t_1, v_{stk} is the stacking velocity estimated from the surface seismic, c is the horizontal distance from the source location to the borehole, and x is the source-receiver offset at the surface. From the CMP stack of the surface data, nearly all the events above 2 seconds are horizontal, and there is little lateral variation in the stacking velocity. So, it is reasonable to use Equation 3 in this case. Here t_1 is measured directly from downgoing wavefield in the VSP data, v_a is calculated from t_1 and the depth of the receiver in the borehole, v_{stk} is estimated from CMP gathers of surface data and c is 27 m for the shot gather used.

Fig. 4 shows wavelet and spectrum estimates at time t_1 from VSP data and their counterparts at time t_2 (from *Equation 3*), estimated from surface data by Gabor deconvolution. *Fig. 5* shows the equivalent wavelet and spectrum estimated from the surface data by frequency domain spiking deconvolution and Wiener deconvolution. Inspection shows that the propagating wavelets experience high frequency attenuation and dispersion with increasing time. The wavelets estimated by Gabor deconvolution are more stable than those obtained by the other methods. We also observe that the amplitude spectra from the surface estimates show more attenuation with increasing frequency than the VSP spectra (*Figs. 4 and 5*), as expected.

Wavelet Comparison By Q Filter

To implement the wavelet comparison, we must either filter the VSP wavelets with a forward Q filter or inverse Q filter the wavelets estimated from the surface data. Since quality factors estimated from VSP data are usually more reliable than those estimated from surface data (White 1992), we choose the forward

Q filter approach. After applying a geometric spreading correction to the wavelet estimates, we assume the major differences between wavelets from VSP and surface data are caused by attenuation. If we assume the quality factor (Q) is the same for both VSP and surface data, the spectral ratio of the VSP and surface data wavelets can be written as

$$\frac{S_{sur}\left(t_2, f\right)}{S_{vsp}\left(t_1, f\right)} = e^{-\frac{\pi f\left(t_2 - t_1\right)}{Q\left(t_1\right)} + i\frac{\pi\left(t_2 - t_1\right)}{Q\left(t_1\right)}H(f)}, \quad (4)$$

where $S_{vsp}\left(t_1, f\right)$ is the spectrum of the wavelet estimated from VSP data and $S_{sur}\left(t_2, f\right)$ is the spectrum of the wavelet estimated from surface data. From this equation we can approximate $S_{vsp}\left(t_1, f\right)$ by $S_{sur}\left(t_2, f\right)$ or the reverse. The constant Q value $Q\left(t_1\right)$ can be estimated from the downgoing wavefield in VSP data. Of the many methods available for Q estimation, the spectral ratio approach, in which Q is estimated by linear regression of the log spectral ratio in the frequency domain, is more accurate than others in noise-free cases (Tonn, 1991). *Fig. 6* shows log spectral ratios at different traveltimes t_1 on the VSP data, and the average Q values estimated. The error bar represents the standard deviation between log spectral ratio and its linear regression. The accuracy of Q estimates can also be assessed by comparing a shallow Q filtered wavelet to deeper wavelets (*Fig. 7*). An excellent match is observed in this study, indicating a consistent Q estimate.

Suppose Q is independent of the ray path. Then Equation 4 can be used to filter the VSP wavelets for comparison to wavelets estimated from surface data (*Fig. 8*). At 0.48 s two-way time, the Q filtered VSP wavelet from an equivalent reflector contains higher frequencies. With increasing time, high frequency components are progressively attenuated, and the Q filtered wavelets gradually conform to the wavelets estimated from surface data. *Fig. 9* shows the amplitude spectra corresponding to the wavelets in *Fig. 8*. By inspection, the wavelet estimated by Gabor deconvolution is the closest match to the Q filtered wavelet from the VSP, especially at greater traveltimes.

We also used a normalized cross-correlation method to compare the wavelets estimated from surface data and Q filtered wavelets from VSP data (*Fig. 10*). This result shows that in this case, the wavelets estimated by Gabor deconvolution are a closer match to wavelets from the VSP than those obtained by the other two methods.

Discussion And Conclusions

We have shown a comparison between wavelet estimates from VSP and surface data. The result depends upon many factors, such as the consistency between VSP and surface data, accuracy of Q estimates, quality of data used for wavelet estimation, and accuracy of the deconvolution methods. The most important factor is data quality. Our results are consistent with the hypothesis that Gabor deconvolution can accurately estimate the nonstationary wavelets embedded in real seismic records. These results suggest that Gabor deconvolution is superior to both multi-window Wiener deconvolution and frequency domain spiking deconvolution methods of wavelet estimation.

Acknowledgements

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References

Aki, K., and Richards, P. G., 1980, Quantitative Seismology, Theory and Methods, 2, W. H. Freeman and Company.

Grossman, J. P., Margrave, G. F., Lamoureux, M. P. and Aggarwala, R, 2002, Constant-Q wavelet estimation via a Gabor spectral model: 2002 CSEG National Convention.

Margrave, G. F. and M. P. Lamoureux, 2001, Gabor deconvolution: CREWES Annual Research Report, 13.

Tonn, R., 1991, The determination of the seismic quality factor Q from VSP data: a comparison of different computational methods: Geophysical Prospecting, 39, 1-27.

White, R. E., 1992, The accuracy of estimating Q from seismic data: Geophysics, 57, 1508-1511.

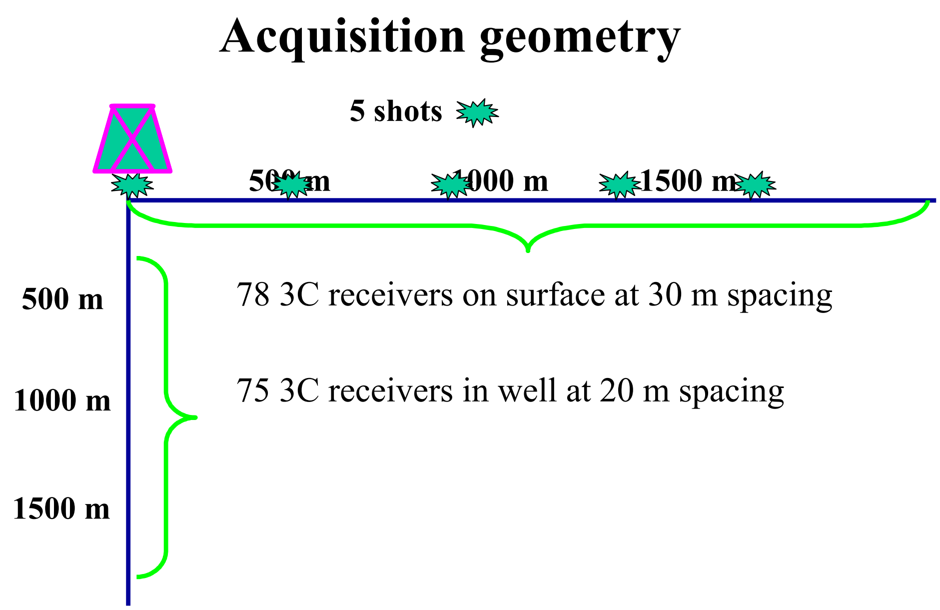

Fig. 1. Joint VSP and surface seismic acquisition geometry.

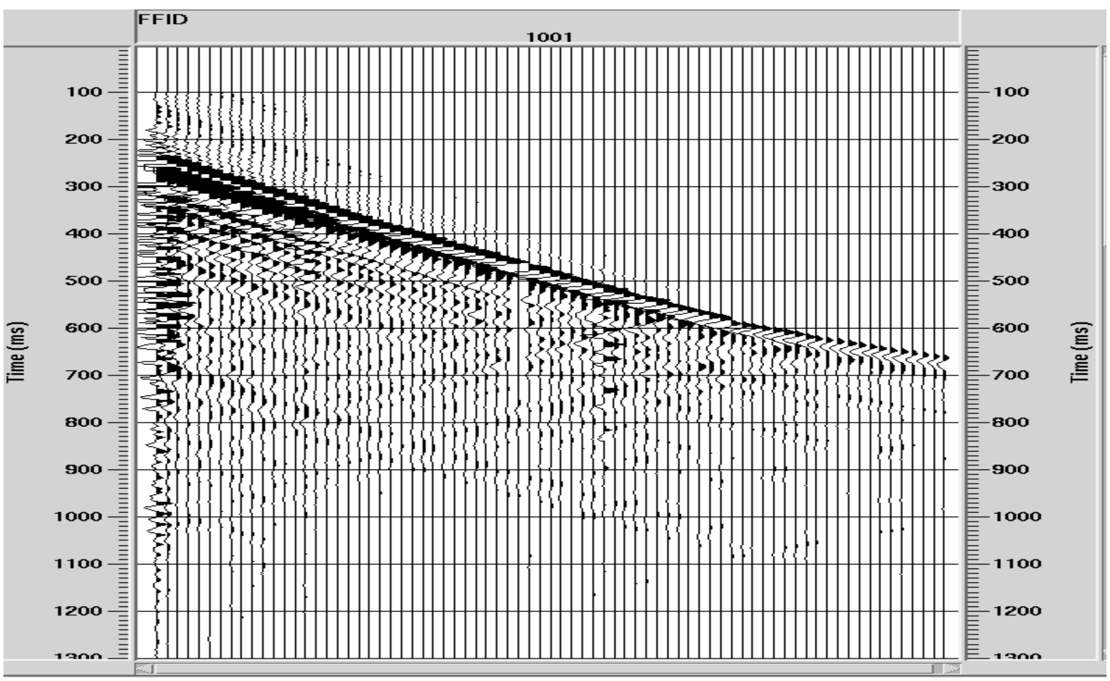

Fig. 2. Zero-offset vertically summed VSP section used in this study. The downgoing wavefield was separated and windowed to estimate the propagating wavelet.

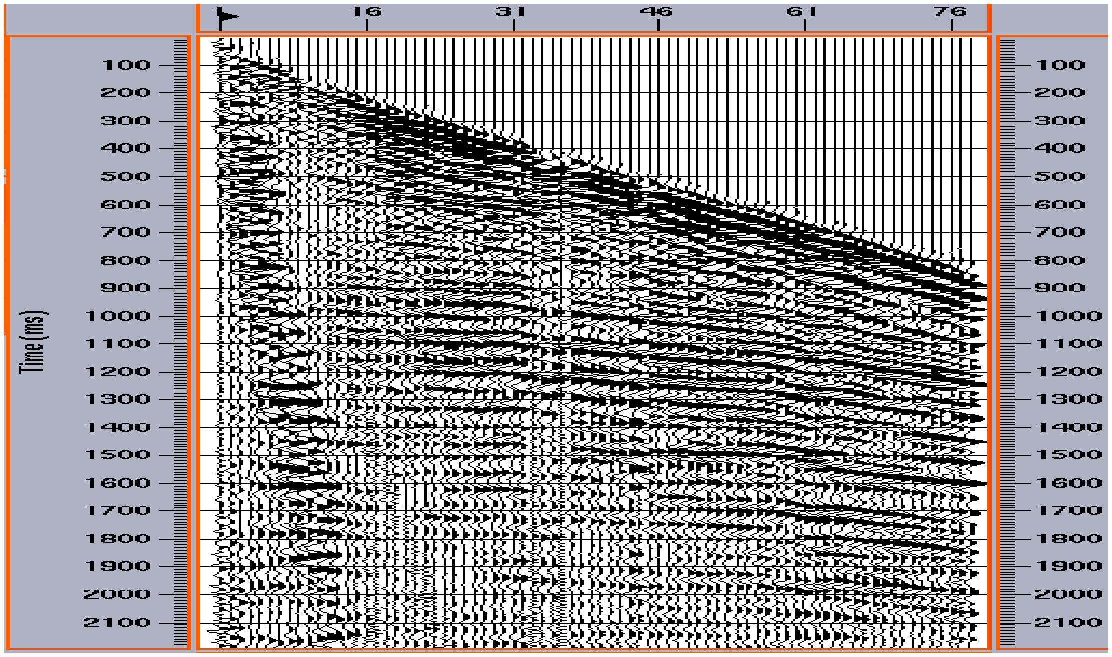

Fig. 3. Noise suppressed source gather for a shot located 27 m from the borehole. Traces 21 to 30, which have a high signal-to-noise ratio, were chosen for propagating wavelet estimation.

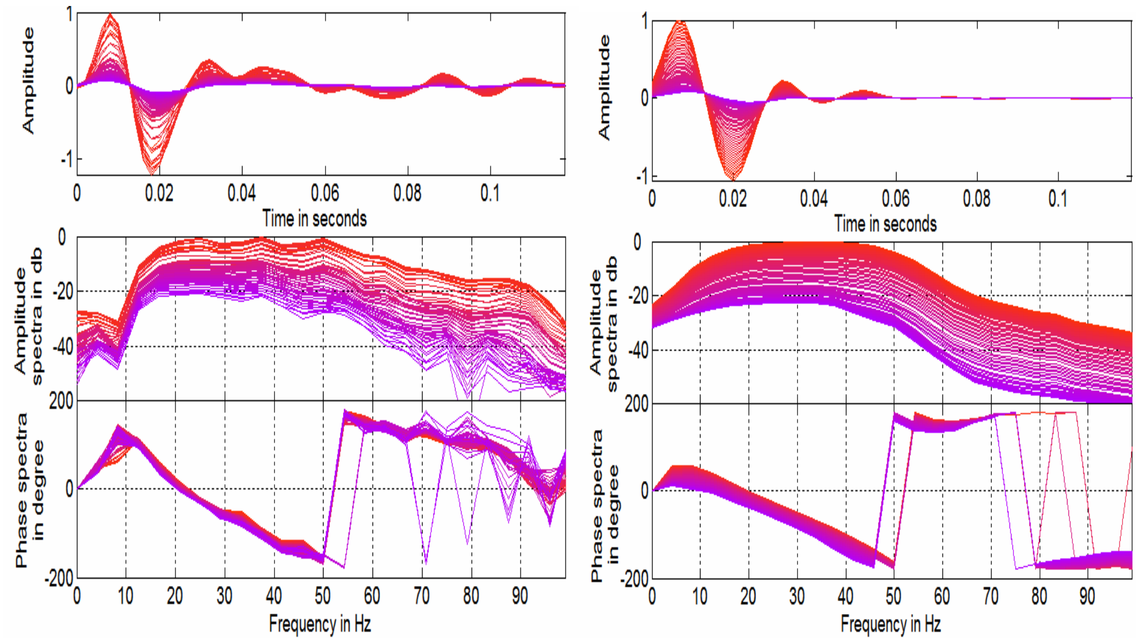

Fig. 4. Wavelet and spectrum obtained from VSP downgoing waves (left), and their counterparts estimated from surface data by Gabor deconvolution (right). High frequencies are more attenuated on the surface data than on the VSP data.

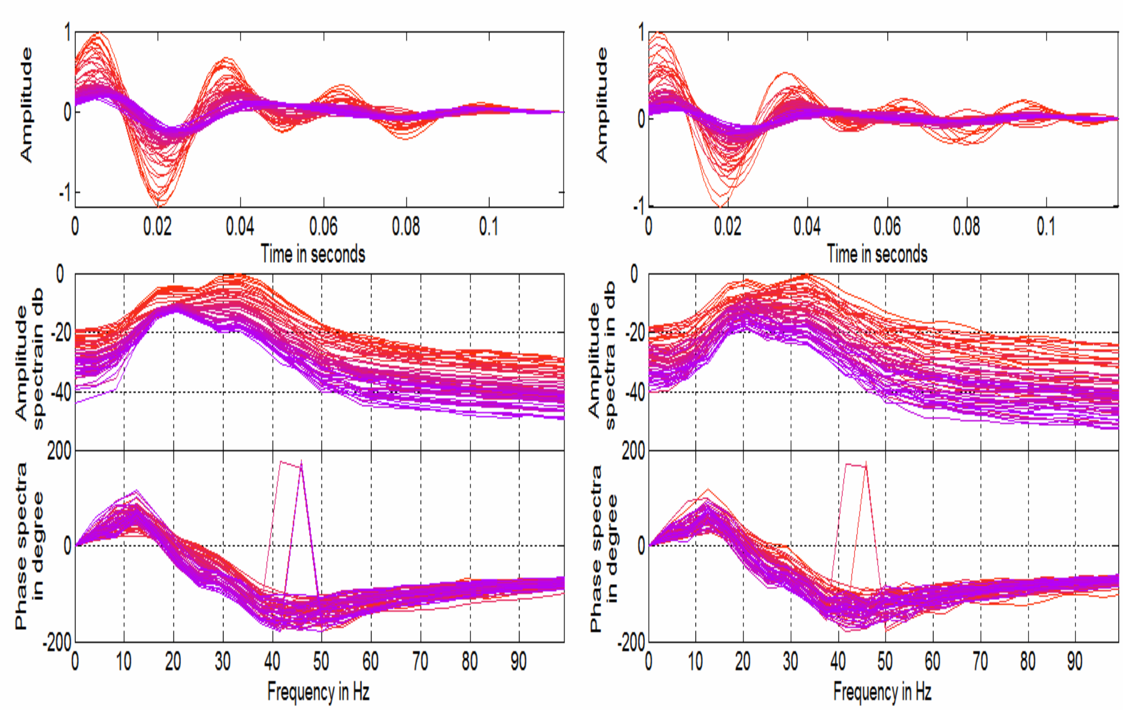

Fig. 5. Wavelet and spectrum estimates from frequency domain spiking deconvolution (left) and Wiener deconvolution (right) of surface data.

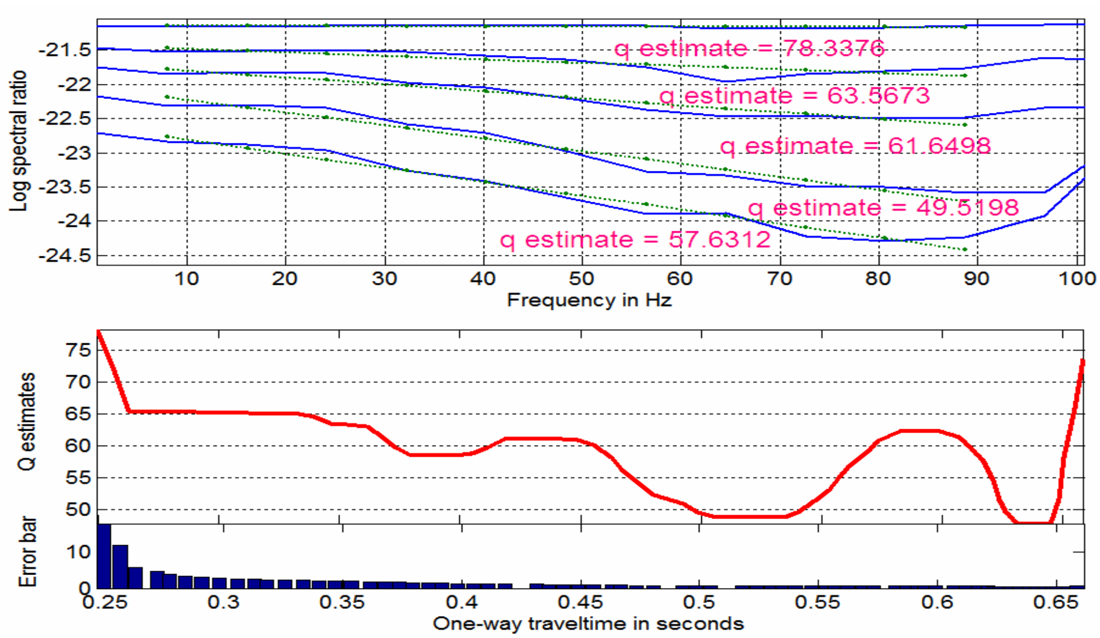

Fig. 6. Log spectral ratio (top), Q estimates (middle) and error bar (bottom) for Q estimated from VSP data. The reference spectrum is the spectrum of the first wavelet from the top receiver. The estimates ('q estimate', top) are average Q between the top receiver and deeper receivers. Error bars represent the difference between log spectral ratio and its linear regression.

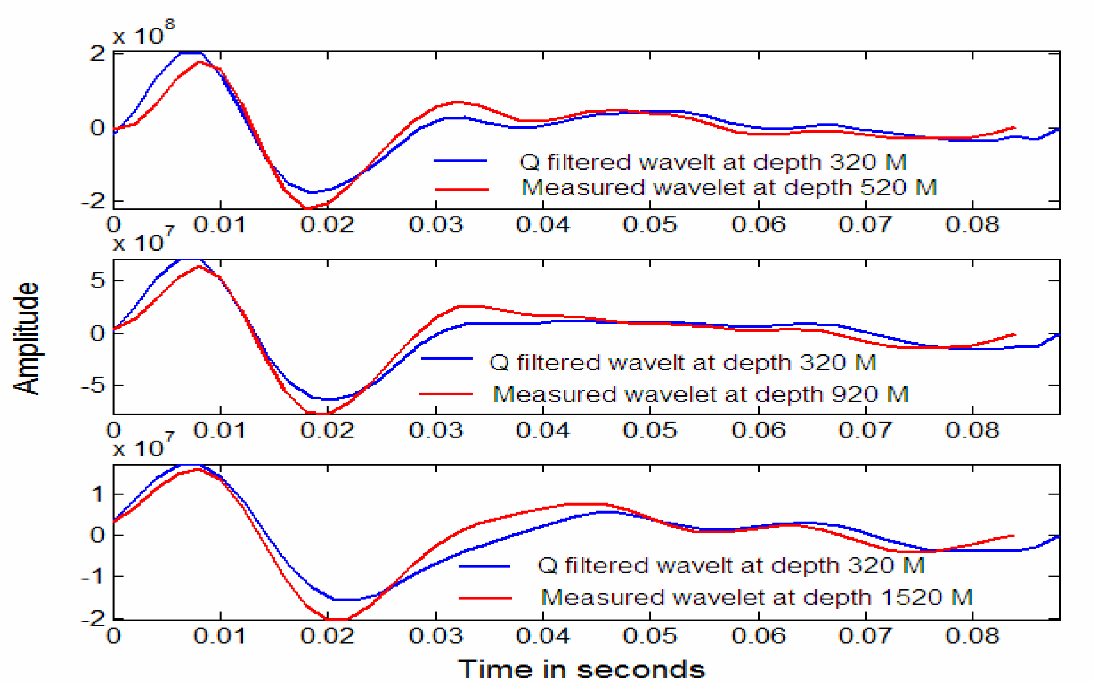

Fig. 7. Q filtered wavelet at 320 m depth compared with measured wavelets at greater depths. The consistence between each pair of wavelets shows that the Q estimates and forward Q filter are reliable.

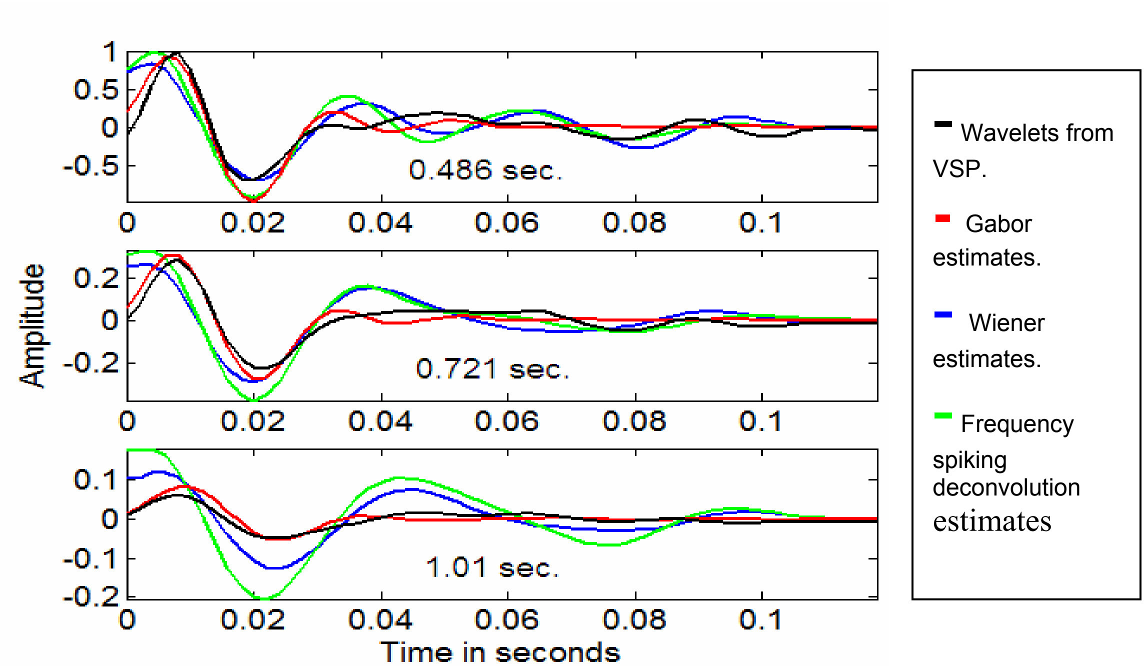

Fig. 8. Comparison of Q filtered VSP wavelets with wavelets estimated from surface data. The x-axis shows the VSP one-way traveltime, with the equivalent two-way traveltime for surface data just above. By inspection, the wavelets estimated by Gabor deconvolution are the closest match to wavelets obtained from the VSP data.

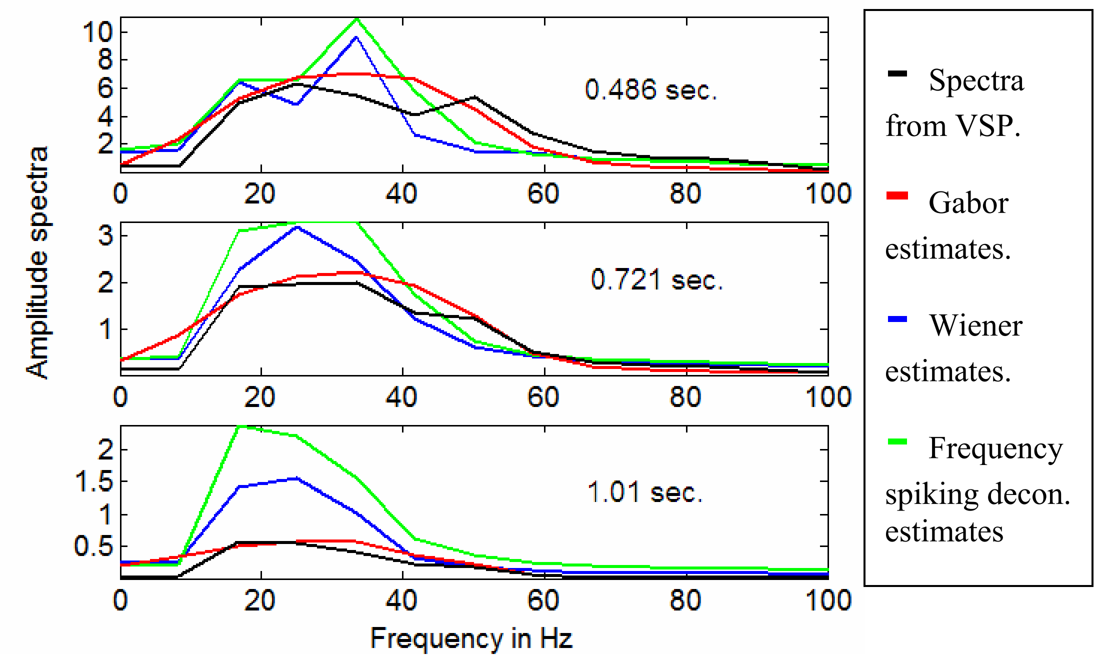

Fig. 9. Comparison of amplitude spectrum estimates. Since Gabor deconvolution uses a Gaussian window and smoothes the time-frequency spectrum, the amplitude spectra from Gabor deconvolution are smoother than spectra from Wiener and frequency domain spiking deconvolution, which use boxcar windows and only smooth in frequency.

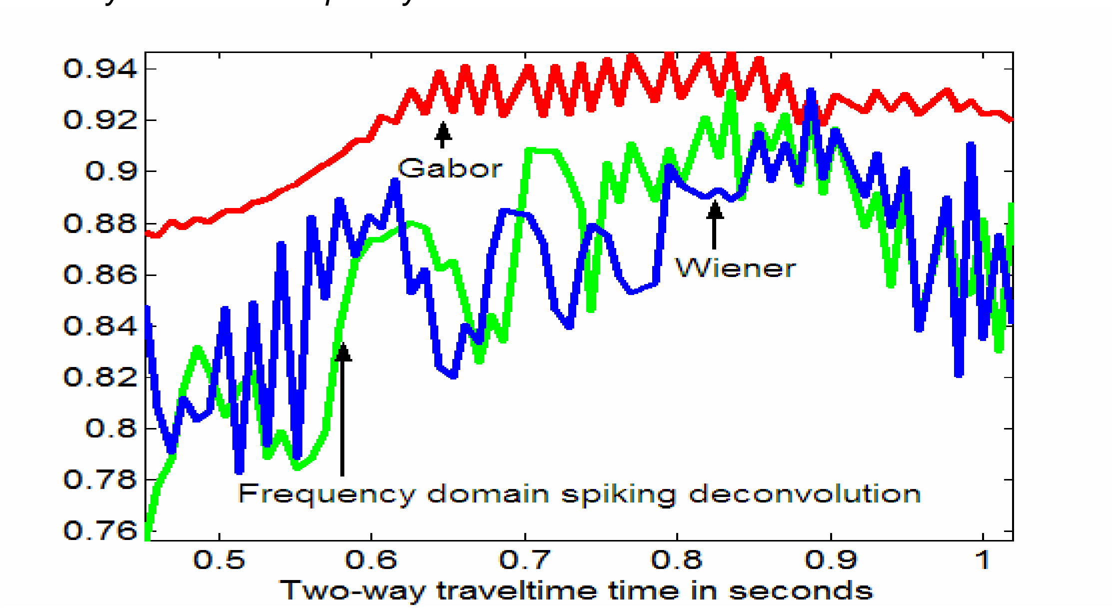

Fig. 10. Peak curves of cross-correlation between Q filtered VSP wavelets and wavelets estimated from surface data by three different deconvolution methods. Again, Gabor deconvolution provides the best results.