

## Investigating the low frequency content of seismic data with impedance Inversion

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### Summary

Acoustic impedance inversion can be a useful tool for reservoir characterization and obtaining rock properties from seismic data. We use a bandlimited inversion methodology that incorporates low-frequency information from well control and does not extend the high frequencies beyond that in the seismic data. The transition from low-frequency well-log information to the seismic data spectrum is marked by a cut-off frequency,  $f_c$ . The choice of  $f_c$  depends on the low-frequency content of the seismic data, and it is generally desirable to push  $f_c$  as low as possible to make the inversion less dependent on well control. We use seismic data from a special low-frequency test conducted by CREWES near Hussar, Alberta. For the Hussar data, with 10 Hz geophones and dynamite sources, an  $f_c$  as low as 1.5-2 Hz gives good results. This is relatively low compared to the 5 to 10 Hz that is commonly chosen for most seismic data. Three wells intersect the Hussar line and all were used to calculate inversions as well as a well log that was prepared by averaging the three impedance logs. The average log was found to produce the best inversions with a mean impedance error of 8.5% from .2 to 1.05 seconds, where wells 12-27, 14-27 and 14-35 produced errors of 11%, 10% and 10% respectively over the same interval. Other cut-off frequencies were also examined and the best choice appears to be non-stationary, as frequencies down to 1.5 Hz can be trusted in the shallower section. This study has shown that the Hussar data set has trusted frequencies down to 1.5 - 2 Hz.

### Introduction

In reservoir characterization and in seismic exploration, impedance inversion can be very useful for obtaining rock properties. While the actual seismic data can be used to see reflectivity differences in the reservoir, impedance is better as it is a measurement of the actual properties of the layers whereas seismic data only indicates the contrast in layers at their boundaries. While more sophisticated impedance algorithms exist, simple acoustic bandlimited impedance inversion is very quick and accessible. The accuracy of acoustic impedance inversion can be increased if the seismic band was expanded to include low-frequencies. The Hussar seismic experiment was conducted with the purpose to investigate low-frequency recording in the field (Margrave, et al., 2012).

Recorded in September 2011 near Hussar, Alberta by CREWES (Margrave et al, 2012), the survey compared receiver types (four types of receivers) and source types (four types of sources) at very low frequencies. Data processing by CGGVeritas resulted in a final section for 10Hz vertical component geophones and dynamite source which is used in this study. The processing flow included algorithms that preserved the low-frequency reflection data that is commonly discarded as noise. The data was also migrated using a Kirchhoff migration operator. Three wells intersected this line, two near the south (12-27 and 14-27) and one towards the north (14-35).

The first step in any inversion is data conditioning. For the Hussar data the wells needed to be tied to the seismic data. For this purpose, we first applied an overburden and underburden to the sonic logs. The overburden and underburden were derived from the stacking velocities, and applied to the sonic

logs. An overburden and underburden was also applied to the density log using the stacking velocities and Gardner's equation, with standard parameters (Gardner et al, 1974). The next step was to estimate a preliminary wavelet by fitting a fourth order polynomial to the log amplitude spectra of a seismic average trace. Synthetic traces were then prepared at each well location. During the processing of the data the amplitudes in the shallow section were subdued so a rough tie of well 12-27 was completed and the seismic data was balanced with a time-variant scaling operator. To create a good tie between the seismic data and the synthetic traces the sonic logs of the wells were stretched until key events matched. Figure 1 shows the seismic data and the well ties after data conditioning. An average-well synthetic trace was prepared by aligning, balancing and averaging the synthetic seismograms at each well location. The reflectivity and Impedance for these wells were also aligned and averaged. Now that the data conditioning has been done the acoustic impedance inversion can be undertaken. The next section describes the algorithm used in this inversion.

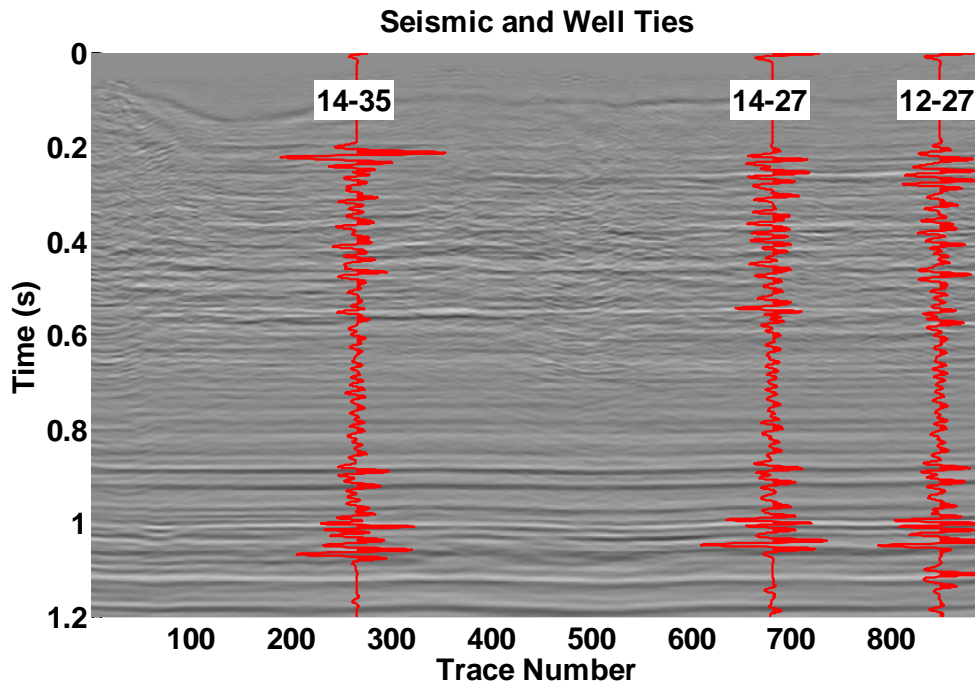


Figure 1: Seismic data and well ties for the dynamite and 10Hz geophones after migration, balancing and well ties.

## Theory

Final seismic sections present an estimate of reflectivity, which is an interface property; however, an acoustic impedance inversion of the reflectivity estimate makes impedance, an inherent rock property, available for analysis. From impedance the velocity, density and other rock properties can be derived. Depth conversion is also possible using the calculated velocities from impedance (Lindseth 1979). Simple acoustic impedance inversions can be computed using the BLIMP (BandLimited IMPedance) algorithm (Ferguson and Margrave, 1996). This method uses the following steps to compute the inversion:

- Compute the linear trend of the impedance log and remove it to help reduce edge effects introduced during Fourier domain calculations.
- Compute the Fourier spectrum of the modified impedance log.
- Apply a bandlimited integration filter to the seismic trace and then exponentiate the result of the filter. The bandlimited integration filter's limits are selected by the user.
- Compute the Fourier spectrum of the integrated and exponentiated seismic trace (3).

- Determine a scalar that matches the mean power from the spectrum of the impedance log (2) to the spectrum of the integrated seismic trace (4).
- Multiply the spectrum of the integrated seismic trace by the scalar determined in (5).
- Apply a low-pass filter to the impedance log spectrum (2) and add to the scaled seismic spectrum (6). The low pass value is called the low-frequency cut-off,  $f_c$ , and is selected by the user.
- Inverse Fourier Transform the result in (7).
- Add the linear trend that was removed in (1) to generate the completed impedance result.

The transition from low-frequency well information to the seismic data spectrum is controlled by a choice of cut-off frequency  $f_c$ . Ideally  $f_c$  should be as low as possible so that most of the inversion is determined by the seismic data; but some well information, usually just a trend, is always required.

### Hussar Impedance Inversion

For the Hussar data set the low-frequency cut-off needs to be defined. Low-frequency cut-offs ranging from 0.5 Hz to 10 Hz, every 0.5 Hz were tested using each of the four wells, 12-27, 14-27, 14-35 and the average well. During this testing the average well had the least amount of error and will be used for advanced testing. Figure 2 shows the test section where the average well is used. To determine how close the inversions are approaching the well impedance a reference filtered impedance trace that is entirely from the well is plotted in the very right and left columns that are separated by a dashed line from the rest of the impedances. This filtered impedance comes from the respective well and has been filtered using the matching filter. To evaluate the cut-offs more numerically the white line in Figure 2 shows the difference between adjacent inversion columns. From this we can pick the point at the apex of the L-curve, which is estimated to be 2 Hz, the optimal low-frequency cut-off. However, it may still be possible that lower frequencies still produce plausible results.

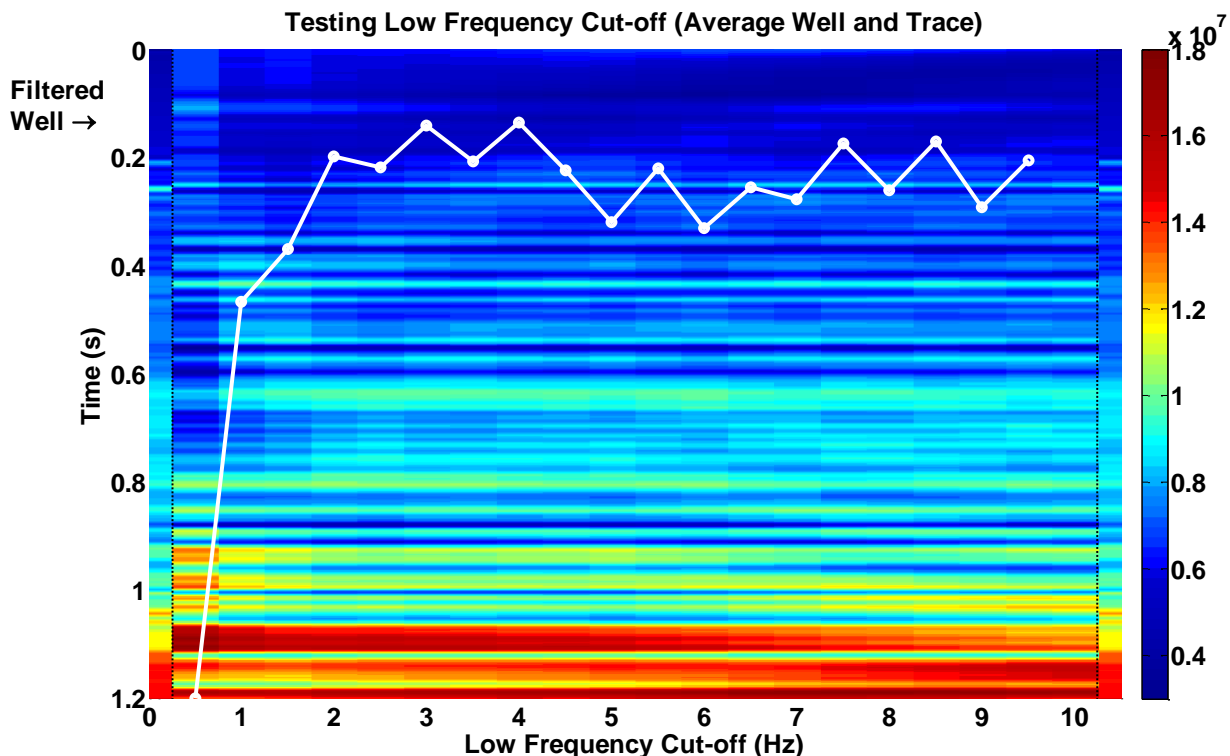


Figure 2: Frequency test to determine the best low frequency cut-off when using the impedance log from the average well. For comparison the filter impedance from the average well is shown at the very right and left of the section. The white curve shows the normalized difference between adjacent inversions.

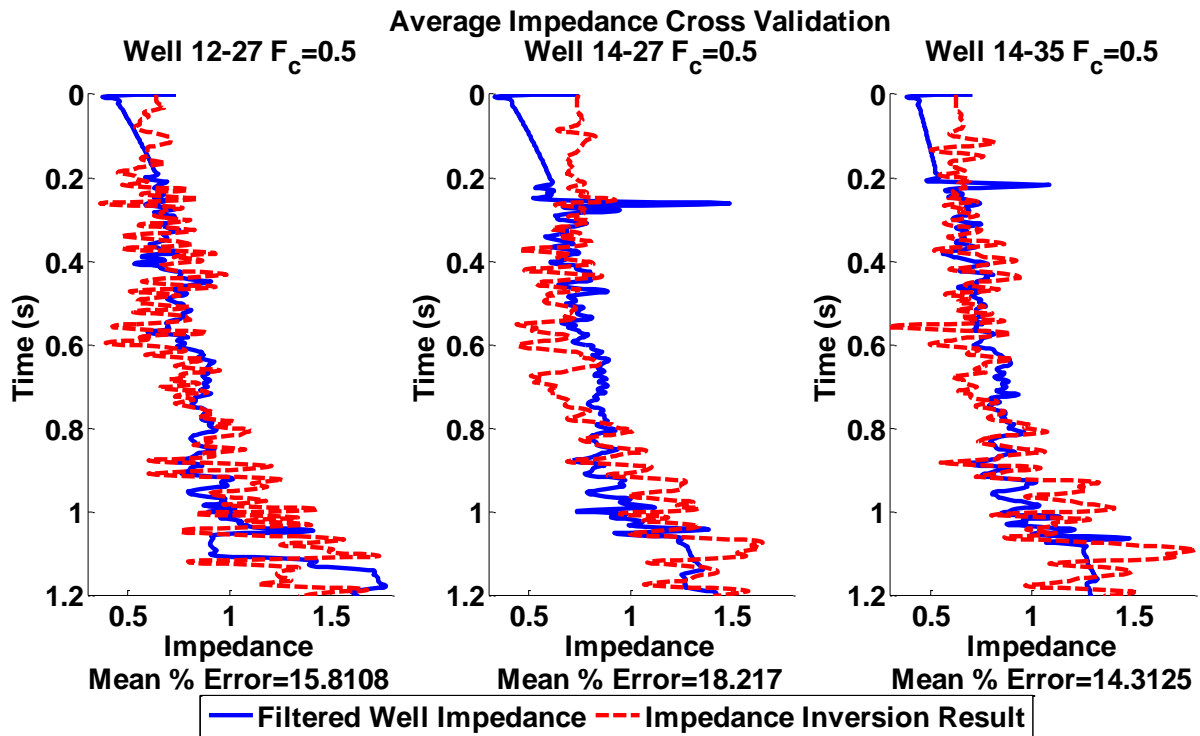


Figure 3: Cross-validation test using a low-frequency cut-off of 0.5Hz

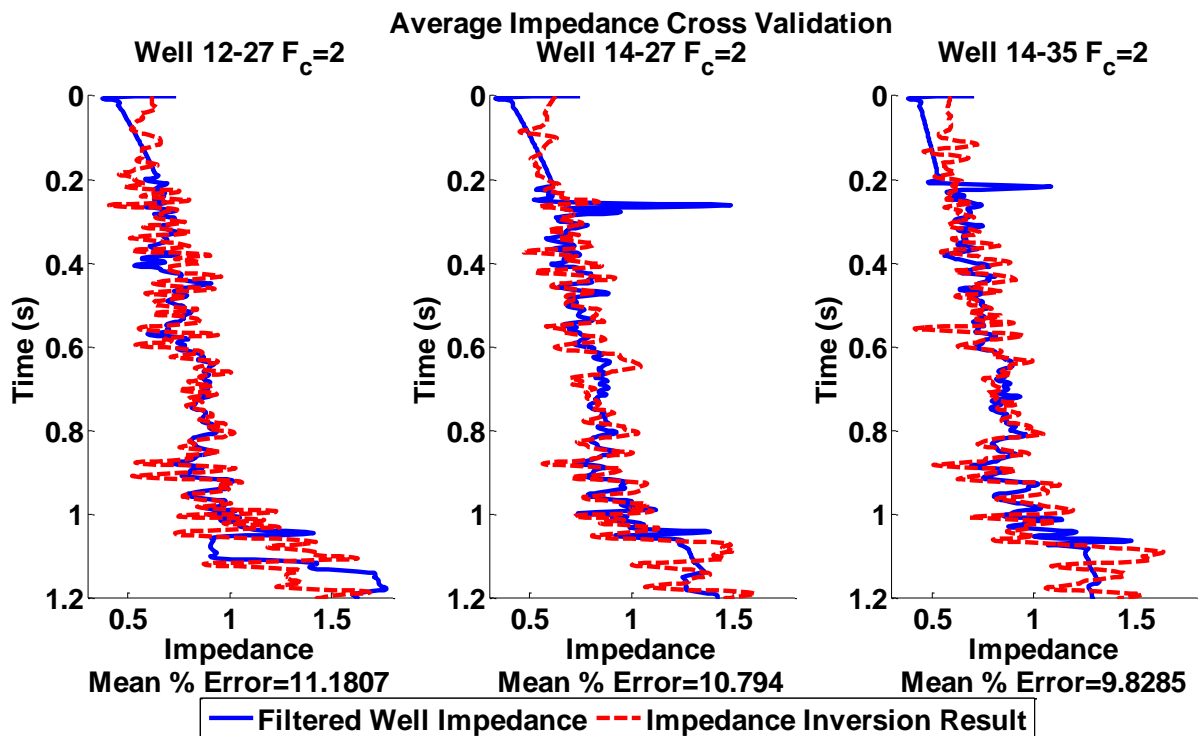


Figure 4: Cross-validation test using a low-frequency cut-off of 2.0 Hz

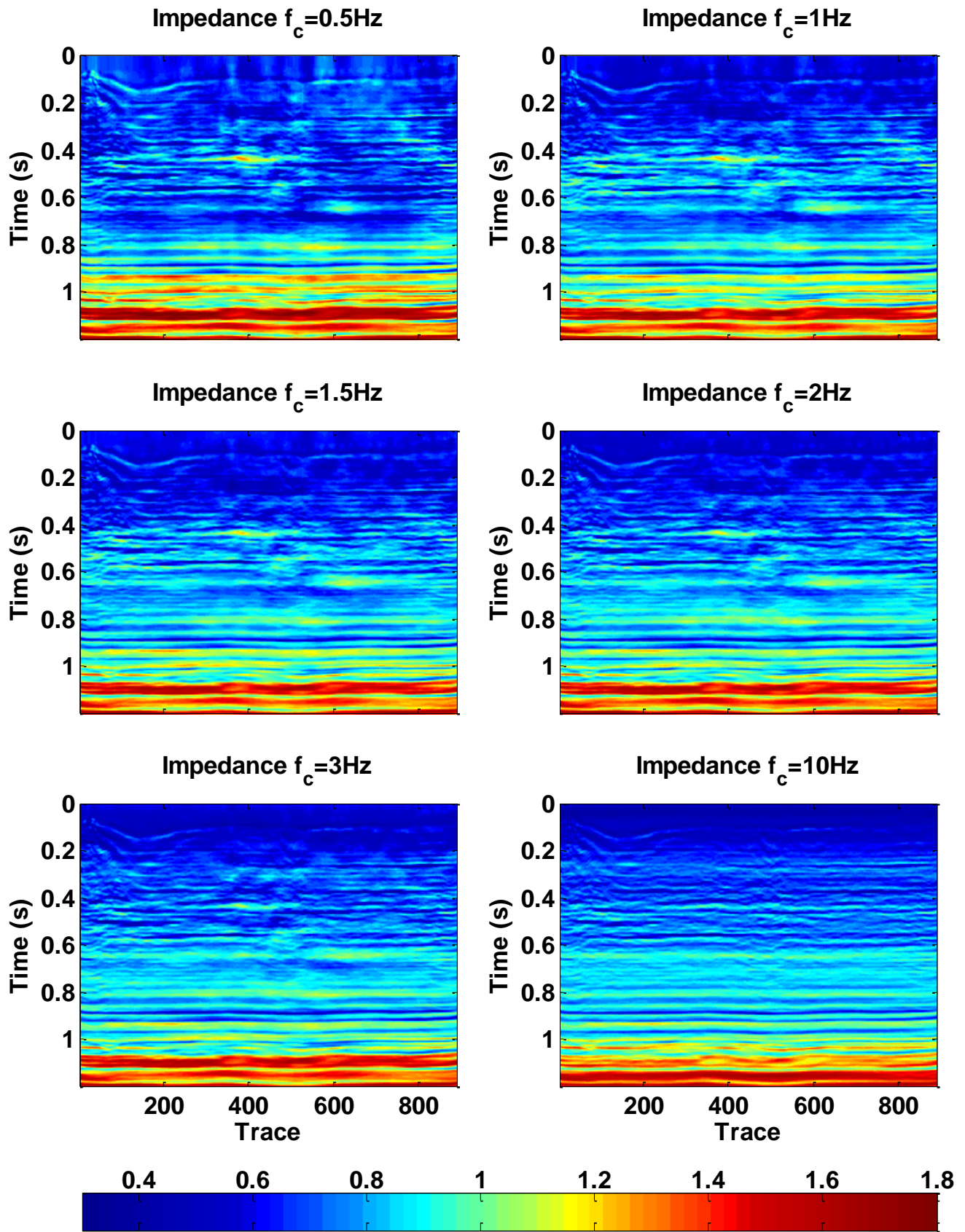


Figure 5: Impedance inversion sections using low-frequency cut-offs of 0.5, 1.0, 1.5, 2.0, 3.0 and 10.0 Hz

To see how the inversion compared with the actual impedance from the wells, cross validation plots were prepared. Figure 3 shows the result for the impedance result using a low-frequency cut-off of 0.5 Hz. This result does not match up with the well log at all whereas the result using a cut-off of 2 Hz better correlates to the well impedance, Figure 4. Figure 5 shows the seismic section inverted using the average well and various cut-off frequencies. From this we can see that where  $f_c=0.5$  Hz the results is very erratic and dissimilar from the other results. The result where  $f_c=10$  Hz is very smooth which indicates that there is too much frequency input from the well. The results where  $f_c=1.5$  Hz and  $f_c=2$  Hz are almost indistinguishable which suggests that we can push the low-frequency cut-off to 1.5 Hz.

## Conclusions

The two most important things to consider when using any impedance inversion incorporating well control are the low-frequency cut-off and the impedance log that is used. In this study we found that a low-frequency cut-off as low as 1.5 - 2 Hz could be used. Using the impedance log from well 12-27, the average error for three cross-validation tests was 11%. For the impedance log from well 14-27 the average cross-validation error was 10%, and the average cross-validation error for the impedance log from well 14-35 was 10%. While any of these well logs could be used to produce an adequate inversion the average impedance of the three well logs produced the least amount of error during the cross-validation tests at 8.5%. This error is still slightly high; however the error in the reservoir interval (0.8 to 1 s) was only 6.5%. Most of the very high error is located where there is an overburden or underburden attached to the log with external information. This indicates that better choices for overburden and especially underburden are possible. These tests imply that for the 10Hz geophone, dynamite-source data there is reliable reflection signal down to 2 Hz and perhaps lower. Our inversions suggest that that the reflection signal band may extend down to 1.5 Hz with good confidence but signal quality becomes more spatially and temporally variable.

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## References

- Ferguson, R. J. and Margrave, G. F., 1996, A simple algorithm for bandlimited impedance inversion: CREWES Research Report, Vol. 8, No. 21.
- Gardner, G.H.F., Gardner, L.W., and Gregory, A.R., 1974, Formation velocity and density – the diagnostic basics for stratigraphic traps: *Geophysics*, 39,770-780.
- Lindseth, R. O., 1979, Synthetic sonic logs – a process for stratigraphic interpretation: *Geophysics*, Vol. 44, No. 1.
- Margrave, G. F., Mewhort, L., Phillips, T., Hall, M., Bertram, M. B., Lawton, D. C., Innanen, K. A. H., Hall, K. W. and Bertram, K. L., 2012, The Hussar low-frequency experiment: *CSEG Recorder*, Sept., pp25-39..
- Pendrel, J., 2006, Seismic Inversion – Still the best tool for reservoir characterization: *CSEG Recorder*, Vol. 31, No. 1.