Spectral Extrapolation and Acoustic Inversion for the Characterization of an Ultra-Thin Reservoir

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Summary

In this paper, we present an ultra-thin gas reservoir seismic inversion study onshore Louisiana that includes seismic conditioning, spectral extrapolation and rock property inversion for acoustic impedance. The study was carried out using prestack seismic gathers and one well with sonic and density logs. The objective was to image the vertical and lateral extent of the gas-charged sand package with a thickness of nine meters (27 feet) at the well. The acoustic impedance inversion result using the spectrally extrapolated seismic data shows an improved match with the measured log in comparison to the conventional seismic data, allowing a more accurate delineation of the ultra-thin reservoir sand.

Introduction

A comprehensive workflow *(Figure 1)* was carried out on a prospect located in Gulf Coast onshore Louisiana. The prospect is part of a downthrown, three-way closure at a depth of nearly 5,000 meters (16,404 feet). The geology at the reservoir level is highly faulted and complex, making seismic imaging and drilling wells a challenge. The reservoir is a gas-charged sand package with a thickness of nine meters (27 feet) at the well location, overlain by a series of shale layers.

The data available includes 3D seismic offset gathers, processing velocities and one well with sonic and density logs. With a dominant frequency of approximately 15 Hz at the reservoir, the seismic data were insufficient for determining the lateral distribution of the reservoir. To overcome this obstacle, a spectral extrapolation algorithm based on spectral inversion was developed and applied to the data following a rigorous gather conditioning process. The spectrally extrapolated seismic data were then inverted for acoustic impedance and compared to the acoustic impedance inversion of the input seismic

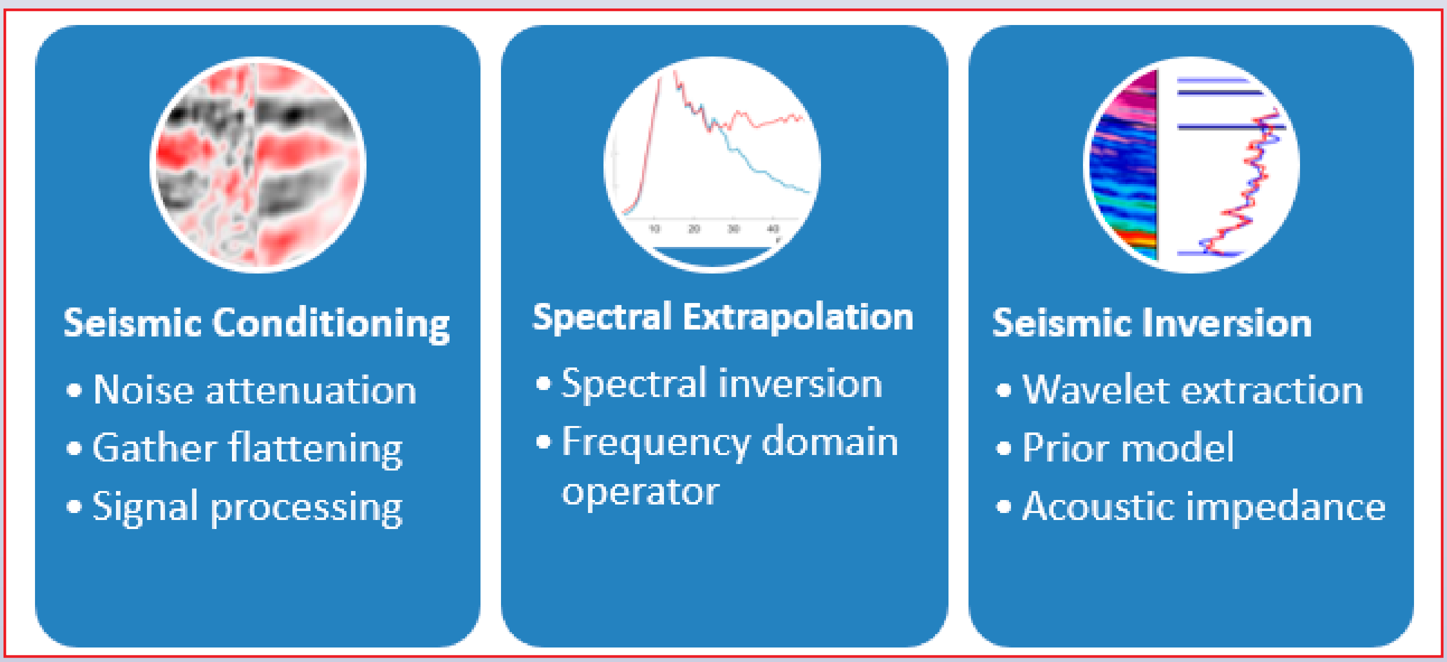

Figure 1: Three main parts of the processes used in the reservoir characterization.

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data. The result shows a high correlation with the well data and is considered fit-for-purpose for post inversion processes and an estimation of hydrocarbons-in-place.

Seismic data conditioning

Seismic data conditioning is central to inversion for rock properties, although it does not fully compensate for the lack of high-quality data acquisition and processing work. The main challenges we faced in our attempt to prepare the data for spectral extrapolation and acoustic inversion included improving the S/N ratio, attenuating small move-out multiples, aligning the gathers and eliminating spatially aliased energy.

To address these challenges, we applied a seismic data conditioning workflow *(Figure 2)* that began with a high-resolution radon transform to reduce incoherent noise and remove internal multiples. Next, residual moveout correction was applied to better align the events prior to stacking.

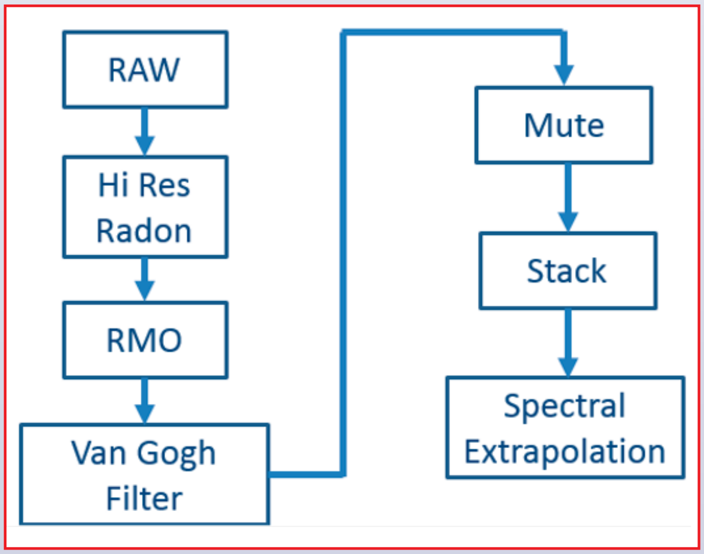

Figure 2: Conditioning workflow applied to the offset gathers prior to spectral extrapolation.

To improve the S/N ratio without sacrificing amplitudes, a non-linear, anisotropic diffusion (Van Gogh) filter with edge preservation (Fehmers and Hocker, 2003) was used to increase the coherency as well as enhance the discontinuities in the data. The last step in our workflow was to suppress the longest offsets with a mute function and stack the near and mid offsets.

In *Figure 3*, we show a comparison of three offset gathers at the well including the raw (a) and the data after seismic conditioning (b). The result of our conditioning attenuated the noise and multiples that contaminated the seismic data, thereby preparing it for spectral extrapolation and acoustic inversion.

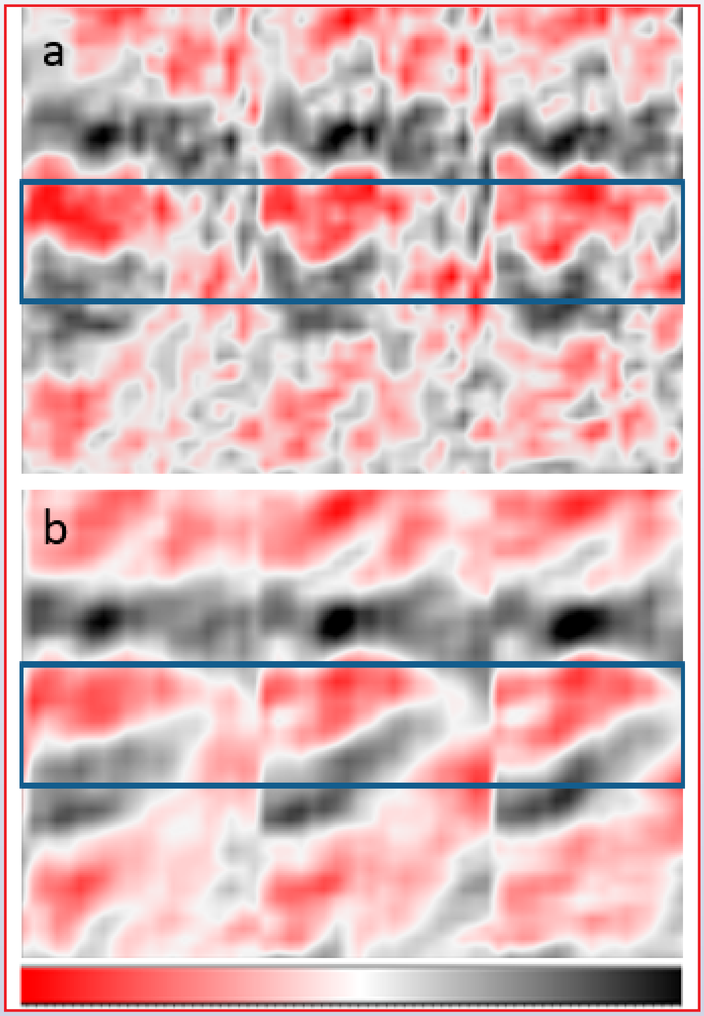

Figure 3: Comparison of three offset gathers at Well A including (a) the raw data and (b) after seismic conditioning.

Spectral extrapolation using spectral inversion

Given the input seismic frequency content, the thickness of our reservoir is well below the seismic

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tuning thickness. For this reason, a spectral extrapolation algorithm based on spectral inversion was applied (Puryear and Castagna, 2008). This process may be used for estimating amplitudes at frequencies near or below the noise threshold in the seismic data, taking advantage of the harmonic resonance phenomenon. Partyka et al., 1999 and Marfurt and Kirlin, 2001, show that the spacing between spectral peaks and notches is exactly the inverse of the layer thickness in the time domain. Knowing this, the repetition of reflectivity patterns in the bands of the spectrum allows one to predict bands outside the seismic spectrum, according to patterns linked to the reflectivity in the seismic band.

Figure 4 illustrates the ideal amplitude response versus frequency for three thin layer models with varying reflectivity ratios in the absence of a wavelet. The thickness of the modeled layer can be estimated from the spacing between spectral notches.

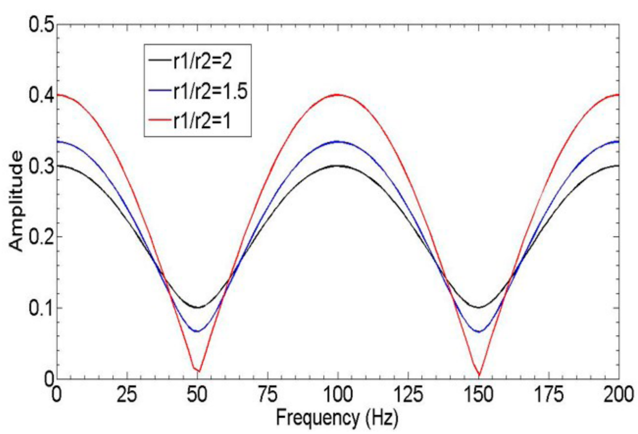

Figure 4: Amplitude response versus frequency for three thin layer models with varying reflectivity ratios. The acoustic impedance of each layer increases with depth.

For our dataset, a subset of the conditioned input seismic was spectrally inverted to derive a reflectivity series estimate in the target zone. Next, a frequency domain shaping operator was applied to modify the band of the reflectivity, preserving high frequencies while maintaining the shape of the original seismic band. In this example, the data were not extrapolated to the lower band since the objective was acoustic impedance inversion, which already accounts for low frequencies from the prior model. The output from spectral extrapolation uses a modified version of the input seismic with increased resolution based on the noise level and processing limitations of the data.

Figure 5 shows the amplitude spectrum before and after spectral extrapolation. The frequency content of the spectrally enhanced seismic honors the input seismic and potentially extends the usable bandwidth out to ~ 65 Hz.

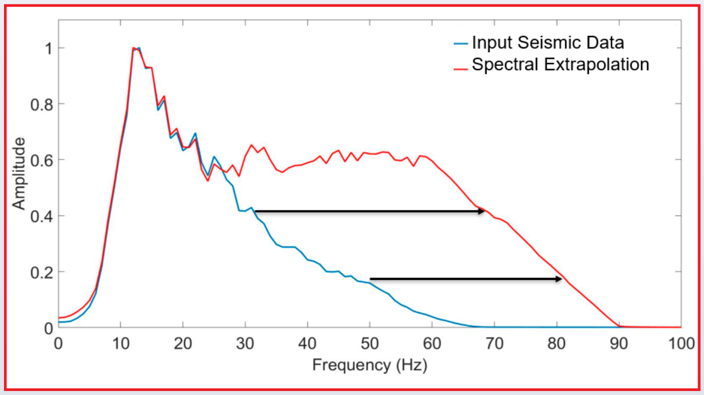

Figure 5: Amplitude spectra of the conditioned stack before and after spectral extrapolation. The spectrally extrapolated data spectrum closely matches that of the input seismic data up to approximately 25 Hz.

Figure 6 compares the conditioned seismic before (left) and after spectral extrapolation (right). As expected, the result reveals features not seen in the

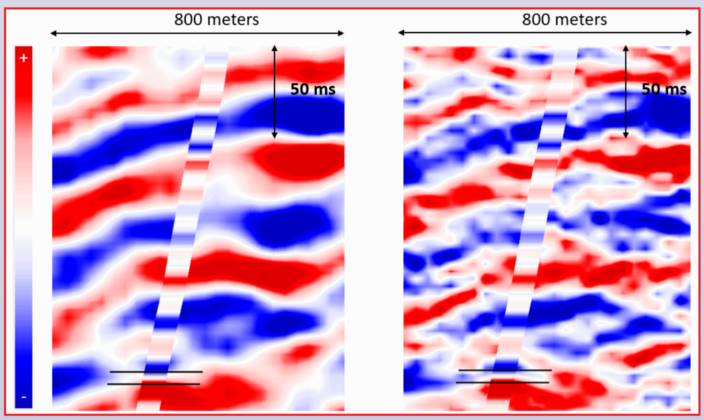

Figure 6: Seismic line with well trajectory before (left) and after spectral extrapolation (right). The reservoir top and base are indicated.

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input seismic. To determine whether these features are geological and can be trusted, the data must be inverted for acoustic impedance (next section). An improved match between the high frequency inversion result and the measured log is key for determining whether the spectral extrapolation was able to enhance the frequency content without generating unwanted artifacts.

Seismic inversion for acoustic impedance

The seismic inversion process begins with wavelet extraction. The objective is to determine a wavelet which best represents the wavelet used in seismic processing. A wavelet may be thought of as a transient superposition of many harmonic waves of different frequencies and amplitudes; a concept known as Fourier synthesis. In seismology, the wavelet is the convolutional operator that links seismic data and the reflectivity of the subsurface. In turn, the goal of seismic inversion is to remove the effect of the wavelet within the seismic bandwidth and recover physical rock properties. The process can also be performed on spectrally extrapolated data, which is analogous to seismic data containing higher frequencies.

The statistical wavelets extracted from each of the two datasets (conventional and bandwidth extended) are plotted in *Figure 7*. No well information was used in the wavelet extraction.

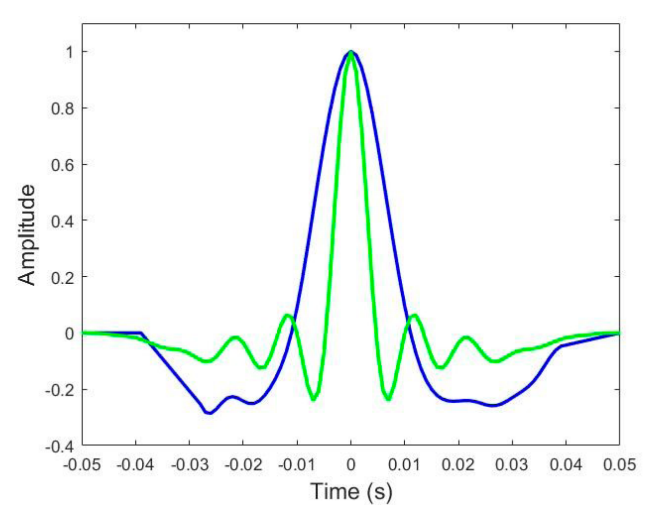

Figure 7: Input wavelet (blue) versus spectrally extrapolated wavelet (green).

A low frequency model (LFM) was generated using the well acoustic impedance. The LFM or a priori model is the starting point of the inversion iteration process. The role played by the LFM is to fill in the lowest frequency gap left by most conventional seismic data acquisition methods (~0 to 10 Hz). Although the LFM contribution is a small part of a full bandwidth acoustic inversion, its role is crucial. Without an accurate background trend, accurate rock property values will not be obtained by the inversion no matter how precisely the mid-to-high frequency information is predicted. The main idea in the LFM process is to apply a low-pass filter to the well data, then interpolate and extrapolate the low frequencies at the well locations to fill the entire 3D seismic geometry. Such interpolation and extrapolation are constrained by the available interpreted horizons and faults, processing velocities and dip fields calculated from the seismic data.

An inverse problem is a mathematical process used for determining the physical properties of a system characterized by a set of model parameters (the model), given the observed response of the system (the data). In seismic inversion for rock properties, the observed response of the system refers to the seismic and well data; the model parameters refer to the subsurface acoustic and elastic properties. In a practical sense, the use of inversion methods allows for 1D borehole measurements to be parameterized into 3D space by analyzing the relationship between the well data and the seismic data. To some degree, the output simulates wireline measurements being recorded at each trace in a seismic survey without the need to drill expensive wells (Leiceaga et al., 2011).

The acoustic inversion algorithm uses a modified version of the Aki & Richards (1980) reflectivity approximation, converting seismic data from interface properties to layers of acoustic impedance. The inversion is based on a convolutional model, generating synthetic seismic data via an iterative process which seeks to minimize the error between observed and modeled seismic (Ma, 2002).

Figure 8 shows the inversion result using the conditioned seismic (left – 4ms sample rate) versus the inversion using the seismic with spectral extrapolation (right – 1ms sample rate) as input. The increased level of layer detail is validated

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by the improved match at the well. Note that the acoustic impedance log was only used to fill in the low frequencies in the inversion process. The wavelets used were statistical, which helps validate the increase in resolution of the seismic and the high definition acoustic impedance.

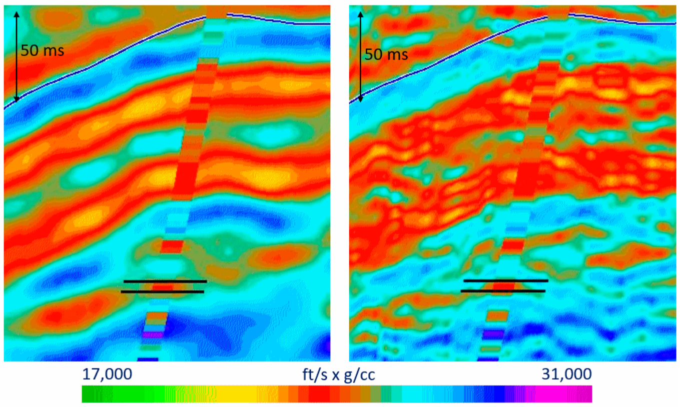

Figure 8: Inverted acoustic impedance section comparison at the well before (left – 4ms sample rate) and after (right – 1ms sample rate) spectral extrapolation. The reservoir top and base (8 milliseconds apart) are indicated along the trajectory. Note the improved match and higher frequency content in the spectrally extrapolated acoustic inversion.

Conclusions

The results obtained show how advanced technologies such as spectral inversion can achieve success in resolving an ultra-thin reservoir that was previously thought to have a seismic character unsuitable to carry out a proper reservoir characterization. The seismic conditioning workflow applied to the data attenuated the multiples and random noise polluting the seismic. Next, a spectral extrapolation algorithm was applied, improving the frequency content of the data. The results from the spectral extrapolation were verified by the improved match between the well acoustic impedance and the bandwidth extended inversion volume. For data having a higher S/N and a wider initial band, greater extension of the bandwidth is possible.

Acknowledgements

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