Adding value and breathing new life into difficult onshore seismic through a novel bandwidth extension approach

Marianne Rauch[1]*, Umberto Barbato[1], John Castagna[2] and Alex Fick[3] showcase the effectiveness of a novel bandwidth extension technique applied to a newly reprocessed 3D dataset from onshore USA.

Abstract

Onshore seismic data is often challenged by high noise levels and limited resolution, even after thorough processing. In this study, we showcase the effectiveness of a novel bandwidth extension technique applied to a newly reprocessed 3D dataset from onshore USA. This approach delivers higher-resolution seismic images and more geologically consistent inversion results. The enhanced dataset improves the accuracy of landing zone selection and supports better planning and execution of the lateral drilling path, ultimately reducing out-of-zone drilling and increasing production rates.

Before the bandwidth extension process, targeted data conditioning was carried out to minimise noise as much as possible. The bandwidth extension itself was achieved using the Multiscale Fourier Transform of the seismic trace, which performs time-frequency analysis across a range of window lengths. This variation in window length helps to capture both local and global amplitude relationships between events, enabling reflectivity inversion that is independent of the seismic wavelet's amplitude spectrum. Since the temporal and spatial variation of the seismic wavelet in reflection data is often poorly understood, this method offers several advantages over traditional seismic reflectivity inversion. No wavelet extraction is required, meaning the inversion process can proceed without relying on well data, seismic ties, or time-depth functions. Additionally, the inversion is sparse and doesn't require a starting model. Since no wavelet is necessary, the method can be applied directly to depth-migrated data.

This inversion technique is particularly valuable for multi-client seismic datasets because it doesn't rely on well data and can be applied over large areas. It enhances the value of existing datasets and revitalises older ones, making them suitable for detailed interpretation and well planning. Well data can then be used to validate the results.

Introduction

TGS maintains an extensive library of both onshore and offshore seismic multi-client data. The dataset used in this study is from the Permian Basin, located onshore USA, and has recently undergone reprocessing for both time and depth using a state-of-the-art processing sequence, which included onshore Full Waveform Inversion (FWI) (see Figure 1).

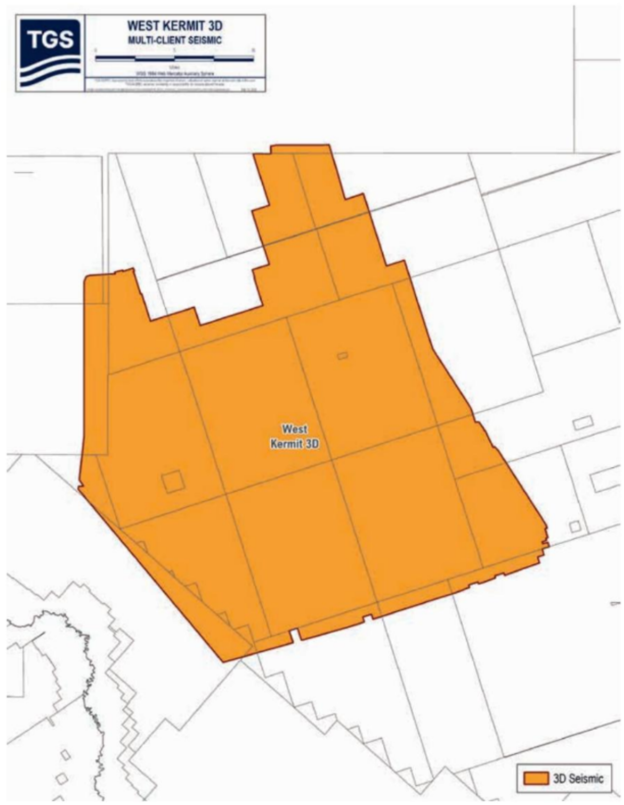

Figure 1 West Kermit survey outline and location.

While this reprocessing was successful, the seismic resolution began to taper off around 40 wavenumbers, making it challenging to map thinner reservoir units accurately. Applying the DeepInvert™ bandwidth extension technique to the pre-stack depth-migrated stack data extended the bandwidth beyond 60 wavenumbers without introducing any artifacts (see Figure 2). The Figure demonstrates that the inversion process does not sacrifice low-frequency data to increase bandwidth at higher frequencies or wavenumbers.

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DOI: 10.3997/1365-2397.fb2025056

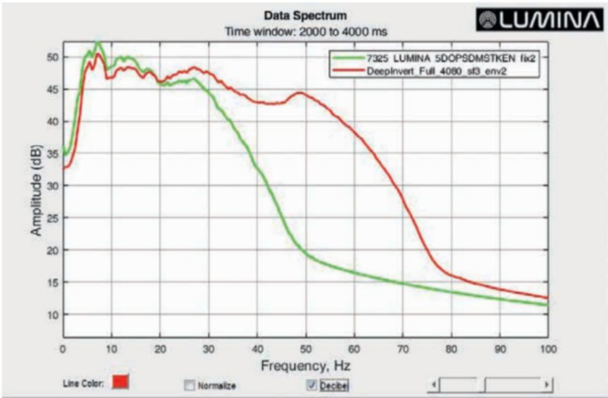

Figure 2 Original frequency spectrum (green), compared to bandwidth extended spectrum in red.

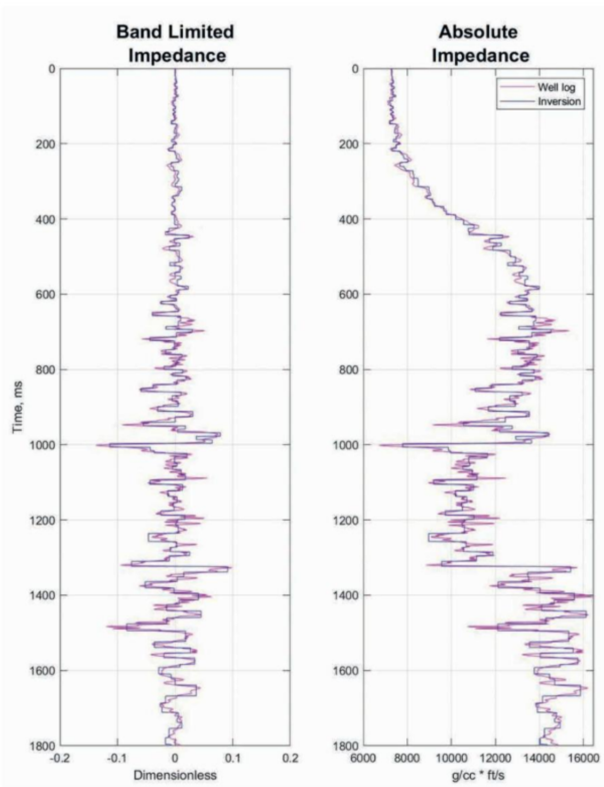

Figure 3 Bandlimited impedance (left track) and absolute impedance (right track) from well logs and seismic inversion without a known wavelet. Inversion bandlimited impedance is converted to absolute impedance by adding the low frequency impedance structure from the well log. Pink = impedance from well log, Blue = impedance from seismic inversion of field data without a known wavelet.

Conventional seismic inversion relies on knowing the seismic wavelet in advance. Determining this wavelet can be a slow, error-prone process, especially when well data have imperfect impedance or time-depth information, or when the wavelet's impedance structure and spatial variation between wells are unknown. Noise in well logs and seismic data, including the presence of interbed multiples, further complicates the extraction of a stable wavelet. Statistical methods for wavelet extraction often depend on assumptions that may not hold, such as white reflectivity or zero phase. However, through training neural networks to predict reflectivity from seismic traces, we found that the longstanding assumption that the seismic wavelet and its variation in time and space are essential for inverting seismic reflection data is not necessarily true, if the inversion problem is structured correctly. In this paper, we describe our technology and demonstrate how it was successfully applied to a typical onshore dataset. Where interbed multiples couldn't be removed, noise was still present, and some target zones fell below the desired frequency bandwidth.

Theory and method

Locci et al (2018) introduced the Multiscale Fourier Transform, which is a generalisation of the Wavelet Transform. The unscaled multiscale transform is simply a Short-Time Fourier Transform (STFT) over variable window lengths.

The variable window lengths of the STFT enable us to identify distinct tuning points of seismic facies variability while addressing one of the main shortcomings of STFT – energy leakage on frequency or time domain. Assuming the dataset to be originally zero phase, this process results in a reflectivity series whose time-frequency-scale analysis of the amplitude spectrum is accurate. The phase variability of the wavelet, which can change gradually both laterally and vertically (time or depth domains) is imbedded in the waveform and also presents variability in the amplitude spectrum; variability, which is also identified by the Multiscale Fourier Transform, and can be derived by combining the real and imaginary components of complex wavelets, as described by Portniaguine and Castagna (2004).

The method involves identifying wavelet-independent features from the multiscale transform by training a multilayer feedforward (MLF) convolutional neural network (CNN) to predict reflectivity series.

Any forward modelling approach can be applied during both the training and inversion processes. The synthetic data can be post-stack or pre-stack and may be 3D in either time or depth (with record times and time shifts replaceable by depths). Potential limitations in the forward model, well logs, or seismic processing can be identified later at validation wells, as no well data is used during the inversion itself. Importantly, once the relevant features are identified, classical geophysical inversion can be applied to these features without the need for retraining for each specific case. The theoretical feasibility of such inversion is demonstrated by Liu et al. (2022).

The seismic bandlimited impedance shows a strong correlation to the bandlimited impedance at wells obtained by removing the well log impedance low frequency trend. Adding this low frequency trend to the seismic bandlimited inversion at the well produces an absolute impedance inversion which compares very well to the measured well log, Figure 3.

Application

The bandwidth extension process described above was applied to the recently reprocessed West Kermit dataset, located in the Permian Basin, onshore USA. The Permian Basin is a major unconventional resource area, but the seismic data in the region is often noisy, with bandwidth typically limited to 40 wavenumbers in conventional datasets. This limitation makes it challenging to accurately identify landing zones and generate lateral pre-drill

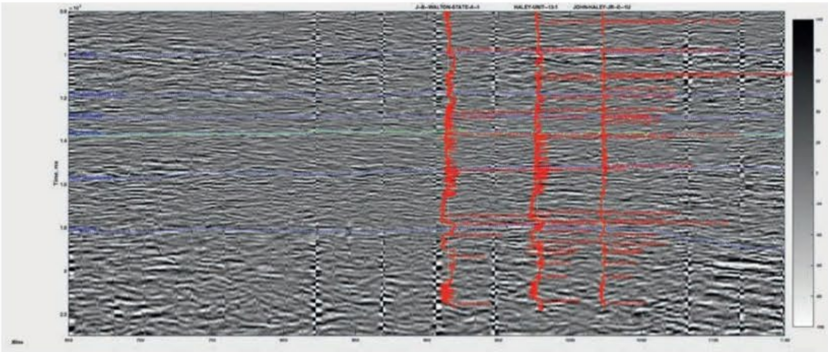

Figure 4 difference plot between input PSDM stack and mild pre-conditioning PSDM stack. The displayed log represents the gamma ray.

plots from seismic data. As most of the prime drilling locations have already been tapped, seismic data is increasingly used to help map and target overlooked zones with good rock properties. Acquiring new seismic data with a significantly higher frequency bandwidth is both time-consuming and costly. By applying a proven bandwidth extension process to existing datasets, many of these challenges can be mitigated.

The dataset was recently reprocessed using a state-of-the-art processing sequence that included pre-stack depth migration and Full Waveform Inversion (FWI). As a result, some additional weak conditioning was applied. Figure 4 shows the difference plot after applying a bandpass filter to remove very high-frequency noise, along with a structural filter. This process eliminated some minor random noise and vertically oriented high-noise bands. This reprocessed dataset served as the input for the bandwidth extension.

In addition to producing a higher frequency/wavenumber seismic dataset, the process also generates a band-limited inversion. As mentioned earlier, no well logs were used during the process, but the results were validated at well locations. The seismic reflection and inversion events were then compared to the well logs to confirm the accuracy of the outcomes.

Figure 5a shows the input dataset, while Figure 5b presents the bandwidth-extended version at the same inline location. This line was chosen as it intersects a well location that has three horizontal well paths. The image in Figure 5a clearly highlights the challenges in resolving some of the thinner intervals within this geological unit.

Figure 5b shows the bandwidth-enhanced dataset for the same line as in Figure 5a. The improved processing has clearly resolved features that were not visible in the original data. The results align very well with the displayed horizontal well paths, with no artificial sidelobes present, and the events can be accurately mapped geologically.

The DeepInvert™ results were used as input for a band-limited inversion (BLI). Figure 6a shows the inversion results at a depth of 13,670 ft, near the Middle Wolfcamp interface. Figure 6b presents the bandwidth-extended results at the same depth interval. The

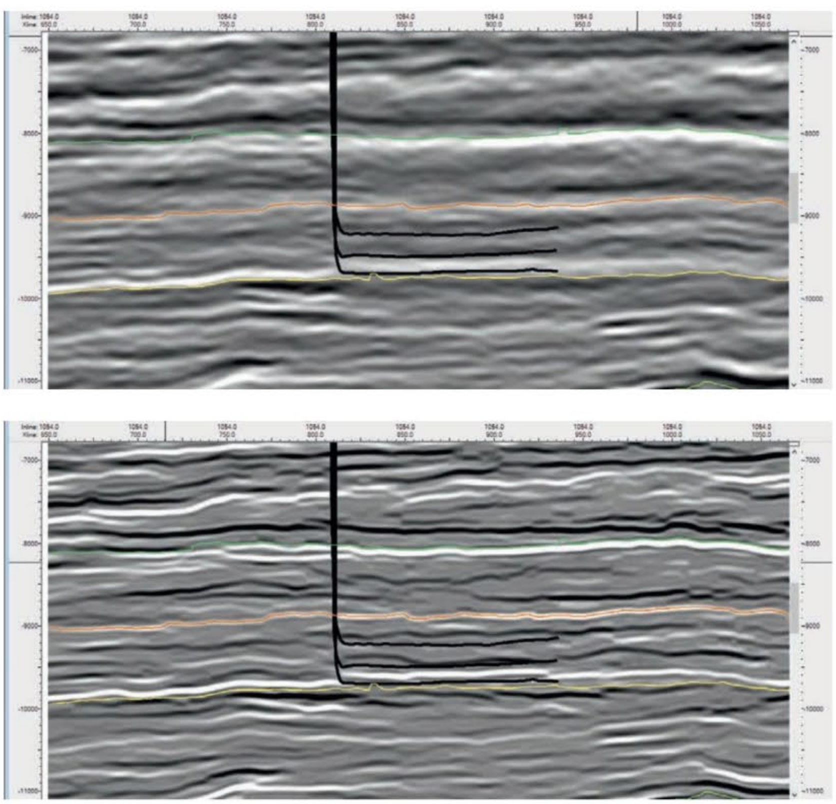

Figure 5 (a) Seismic reflectivity input data of an inline that intersects 1 well with 3 individual horizontal well paths. (b) Seismic reflectivity bandwidth enhanced data of the same inline as is displayed in Figure 5a.

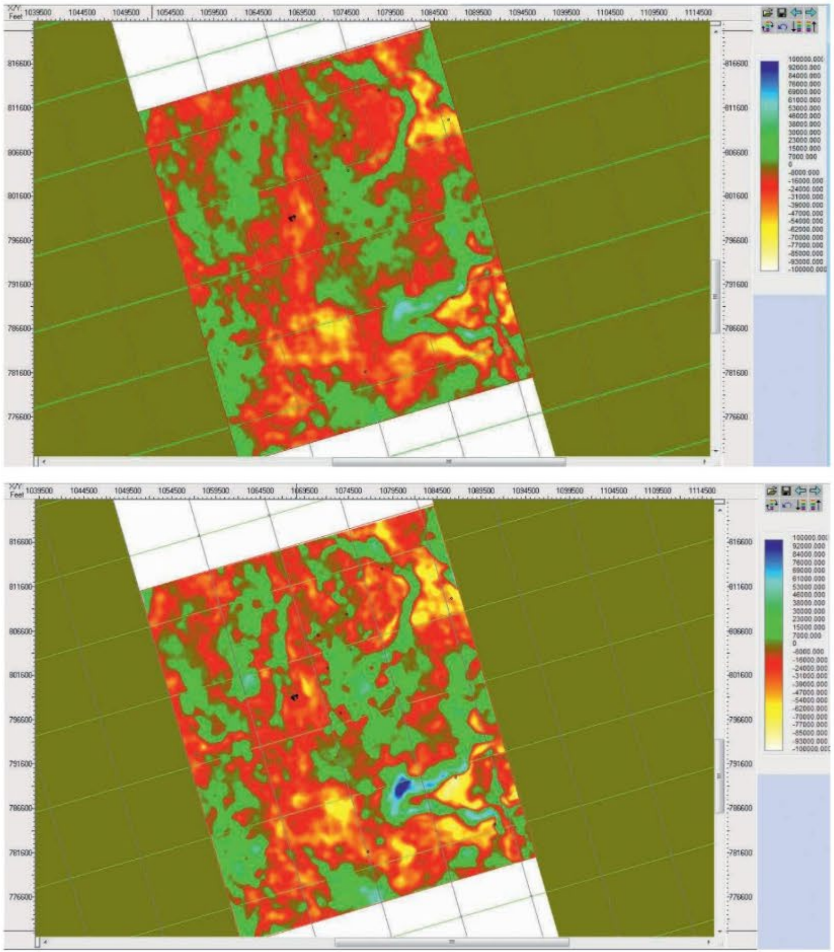

Figure 6 (a) BLI depth slice at 13,670 ft of input data, middle Wolfcamp. (b) BLI depth slide at 13,670 ft of bandwidth extended data, middle Wolfcamp.

bandwidth extension reveals more details and sharpens boundaries, which is the desired outcome and is very useful for choosing landing zones and designing horizontal well paths.

Conclusions

Reflectivity inversion of seismic data can be performed without the explicit a priori knowledge or extraction of the seismic wavelet. The process involves direct, sparse geophysical inversion of features derived from the Multiscale Fourier Transform. Since no training is required for application to a specific dataset, this method is particularly valuable for larger datasets.

The ability to invert seismic data without prior knowledge of the seismic wavelet significantly improves the inversion process. In conventional practices, synthetic ties and wavelet extractions are necessary before inversion, which is not only time-consuming and costly but also inherently inaccurate due to the wavelet's poorly understood and variable nature in terms of time, position, and offset. Typically, constant wavelets are used, assuming that spatial and temporal variations in the wavelet are adequately addressed in processing. In contrast, the applied inversion method does not require the wavelet to be known in advance, making it immune to the effects of actual wavelet variations over time, spatial position, and offset.

This method was applied to extend the bandwidth of the West Kermit onshore dataset, located in the Permian Basin, USA, an area known for its seismic challenges. Despite careful acquisition and seismic processing, the data are generally noisy and lack higher frequencies. By applying DeepInvert™, the bandwidth was increased from around 40 wavenumbers to over 60 wavenumbers. This enhancement revealed previously missing details in the image, and the subsequent BLI inversion clearly displayed sharper boundaries and improved resolution of smaller features.

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