A 2-Stage Approach to Broadband Processing for Improved Stratigraphic Interpretation in the Sergipe Basin, Brazil

Mike Saunders[1], Laurie Geiger[1], Jaime A. Stein[2], T. Altay Sansal[2], John Springman[2]
[1]Spectrum Geo, Inc – Houston, TX, [2]Geotrace Technologies, Inc – Houston, TX

Abstract

The narrow frequency bandwidth found in conventionally acquired marine seismic is due in part to the source and receiver ghosts, which lengthen the source wavelet. Additionally, as seismic energy travels through the earth both low and high frequencies are attenuated, though by different amounts. Recent advances in processing technology allow for conventionally acquired seismic data to benefit from increased bandwidth and corrected ghost wavefields, giving more usable high and low frequencies. This extension in bandwidth can lead to seismic images that reveal more detailed geologic events. We present a 2-stage methodology to broadband seismic processing which includes a pre-stack de-ghosting process and a post-stack bandwidth recovery process.

The Sergipe Basin is a relatively mature hydrocarbon province on the northeast coast of Brazil, comprising 44,370 km² both onshore and offshore. The onshore portion of the basin (12,620 km²) is considered mature, with over 2 billion bbls in place and 816 wells drilled since 1935. Petrobras has made offshore several discoveries since 2010, including the 2010 Barra well (1-SES-158) and the subsequent Barra 1 appraisal well (3-SES-165). The wells targeted oil and gas charged Maastrichtian sandstones that display readily identifiable AVO anomalies on 2D seismic profiles.

Approximately 16,000 km of long offset 2D seismic data was acquired in 2014 using a flat streamer towed at a depth of 15 m. The data was processed through pre-stack time migration using conventional techniques, and through pre-stack depth migration including broadband processing techniques. The broadband processing included a de-ghosting phase applied pre-migration as well as a bandwidth enhancement applied post-migration/post-stack.

We analyze the sequence stratigraphic interpretation of both the conventionally processed PSDM data and the broadband PSDM data in order to quantify the improvement in resolution achieved through broadband data processing.

Introduction

The Barra discovery well was drilled in September 2010, reaching a depth of 6,510 m in 2,341 m of water. Permeability and porosity conditions in the reservoir are excellent at well depths of approximately 4,650 m to 4,750 m, where drill stem tests indicate gas and condensate are present in commercial quantities. The gross thickness of the zone of sandstones encountered in the Barra well is approximately 80 m thick as illustrated in the composite log (Figure 1), from which well tests indicate a high porosity / low density, gas-charged reservoir.

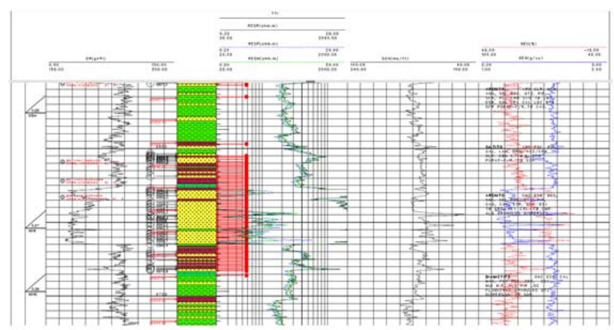

Figure 1 – Composite Log from SES-158 Barra Discovery Well

Two other discoveries in the deepwater area of this basin include the Muriu and Farfan finds, with estimates indicating 3 billion bbl of oil in place. These estimates continue to rise due to other exploration successes, including the 3-SES-186 appraisal well announced in February, 2015. These discoveries are in turbidite channel systems of Mid- to Late Cretaceous and Early Tertiary age, as well as some located in rifted basin fill (Figure 2). It is likely that these stratigraphic hydrocarbon plays extend further outboard to the east and southeast, into a basin floor fan setting. To the northeast of the Sergipe Basin, channel fill sediment plays, rifted basin fill and faulted Paleozoic sediment scenarios exist for more exploration opportunities.

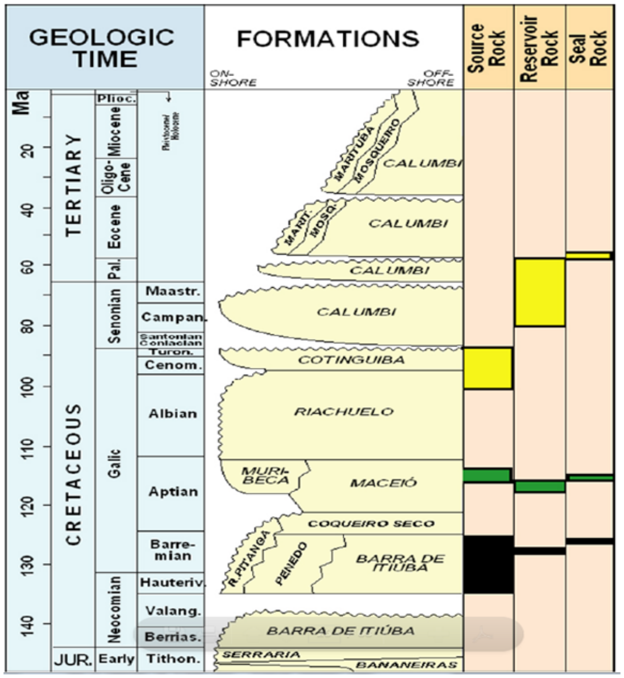

Figure 2 – Stratigraphy column of the Sergipe-Alagoas Basin (Melton 2008)

With conventional seismic data, identification and subsequent interpretation of thin stratigraphic beds such as those found in the Sergipe Basin, have previously been limited by inadequate resolution at reflecting interfaces. In this paper, we demonstrate that de-ghosting and bandwidth extension using the Continuous Wavelet Transform (CWT) technique can produce broadband data that allows for improved identification and mapping of thinner potential hydrocarbon reservoirs, compared to using conventionally processed seismic data.

Broadband Processing

As the seismic signal travels through the earth the loss of bandwidth (high and low frequencies) due to absorption, dispersion, and other viscoelastic effects reduces the resolution of any seismic data. This loss of resolution complicates the interpretability of the data and increases the risk associated with prospecting.

To better identify and map previously indiscernible potential source rock and reservoirs, high frequency, higher resolution data is needed. Recent advances in seismic acquisition techniques allow for gathering wider bandwidth data in the field, however the cost is high compared to conventional methods. An alternative and more cost-effective approach for mitigating the bandwidth limits of seismic data can be done in processing.

According to the Rayleigh criteria, conventionally acquired and processed seismic data is band-limited, thus preventing the identification of beds thinner than ¼ the dominant wavelength. However, Widess (1973) proved that a reflected event does have information within the wavelet that is beyond the dominant frequency of the data, which is indicative of a bed's thickness. In fact high frequencies can be recovered from the data leading to a resolution thickness as thin as 1/8 the dominant wavelength, twice as thin as previously thought.

Figure 3 shows a graph illustrating the potential tuning thickness of seismic data relative to frequency content for a velocity of 3,400 m/s. Typical seismic data acquired with a streamer towed at a depth of 15 m and a source towed at 10 m, such as in the Sergipe 2014 survey examined in this paper, has frequencies limited to approximately 10 Hz to 45 Hz. The logarithmic graph shows that by increasing the usable bandwidth of the data thinner beds can be identified, and the broadband processing methodology applied to the Sergipe data illustrates the effectiveness of this approach.

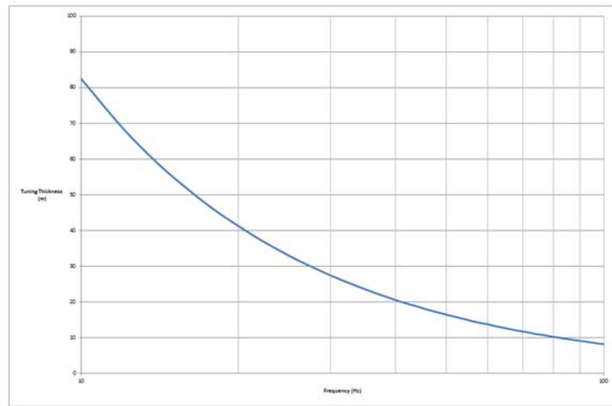

Figure 3: Tuning thickness vs. Frequency (3,400 m/s)

In addition to the loss of usable frequencies due to viscoelastic effects, there are other non-dissipative phenomena that also contribute to the narrowing of the bandwidth, namely interfering patterns produced by the self-interactions of seismic waves. One of the interference patterns that contaminate the input data is known to the oil and gas industry as ghost reflections, and is a consequence of having sunken sources and receivers which produce secondary reflections off the air-water contact. This interference pattern is responsible for variations in seismic amplitudes and frequencies, which can lead to amplitude brightening or dimming of the signal as well as tuning. If left unresolved, these distorted amplitude anomalies could lead to seismic misinterpretation and could also be false indicators of hydrocarbons. The lack of high frequencies results in a blurring of the data as the wavelet becomes broader and flatter, making the exact locations of reflectors more difficult to ascertain. Low frequency loss causes the wavelets to have high frequency side lobes which make the seismic appear "ringy" and produces spurious apparent reflections surrounding the true reflections. Both effects must be corrected in order to achieve broadband, high resolution marine seismic data (Figure 4).

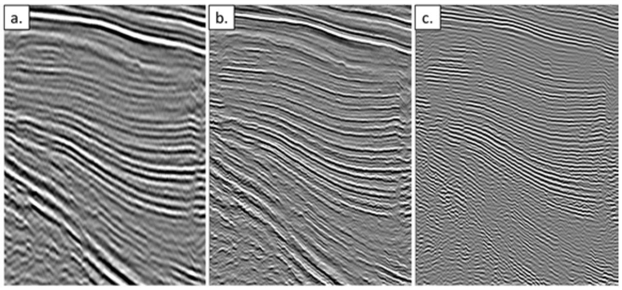

Figure 4: Seismic sections displaying various bandwidths. Panel (a) is deficient in high frequencies making the section blurry. Panel (b) is the full bandwidth section. Panel (c) is deficient in low frequencies making the section appear "ringy".

Broadband processing can be used to address the bandwidth limiting issues identified in this paper. We describe a two-step methodology that 1) eliminates the ghost interference patterns common to conventional 2D and 3D marine seismic data using a proprietary marine de-ghosting technology known as HDBand™, and 2) recovers the low and high frequencies attenuated due to viscoelastic effects using another proprietary technology called BE®. (Hellman et al., 2014, Stein, 2014, Smith et al., 2008).

The data we examine in this paper was acquired in 2014 with a flat streamer 10 km in length and a conventional air gun source, deployed at depths of 15 m and 10 m, respectively. The data was processed through a conventional state of the art marine processing workflow along with the application of broadband processing. This workflow included adaptive noise attenuation, Surface Relative Multiple Elimination (SRME), Radon de-multiple, statics corrections, Pre-Stack Time Migration (PSTM), Pre-Stack Depth Migration (PSDM) and anisotropic corrections. The PSDM velocity model was constructed using multiple iterations of grid tomography, constrained by a detailed geologic interpretation incorporating the passive margin basin architecture. Post-migration enhancements were applied to the seismic data and the CDP gathers were conditioned to suppress incoherent noise and increase seismic signal-to-noise ratios.

A compelling argument can be made that the de-ghosting process should be applied prior to SRME (Brookes et al. 2014, Sablon et al. 2012, and Sablon et al. 2011), however the water bottom multiple is much deeper than the reservoir. Consequently, we took the decision to apply de-ghosting after SRME.

HDBand ™ and BE®

HDBand™ is a technology specifically designed to de-ghost marine data. Traditional seismic trace analysis in the frequency domain uses the Fourier transform, which assumes a stationary input time series. This implies the transformation of local information (i.e. reservoir thickness) into global information (i.e. discrete frequencies within a wavelet). The Continuous Wavelet Transform (CWT) domain is not limited by a stationary input time series assumption, consequently it permits the analysis of both local information and global information simultaneously (Smith et al, 2008). The proprietary de-ghosting technology applied to the data presented in this paper identifies ghost notches in the data spectrum and designs time-varying inverse filters to fill in the notches, including the zero-Hz notch, thereby correcting the amplitude and phase errors caused by the interference patterns. The filters applied to each trace are based on unique characteristics such as source and receiver depths, offset, water velocity, sea state, etc.

In addition to the de-ghosting process, BE® technology was used to compensate for the loss of frequencies due to viscoelastic effects. The bandwidth extension algorithm models the attenuated data as harmonics of the visible frequency band. After using the available wells to zero-phase the seismic data, the harmonics are predicted and convolved with the data to enhance the spectrum into the high frequencies within the limits of Nyquist frequency sampling. Figure 5 shows the application of HDBand™ and BE® to the Sergipe 2014 data. In the inset one can observe the spectra of both the normal bandwidth and broadband data. Broadening of the bandwidth of both the low and high frequencies and the disappearance of the ghost notches is observed.

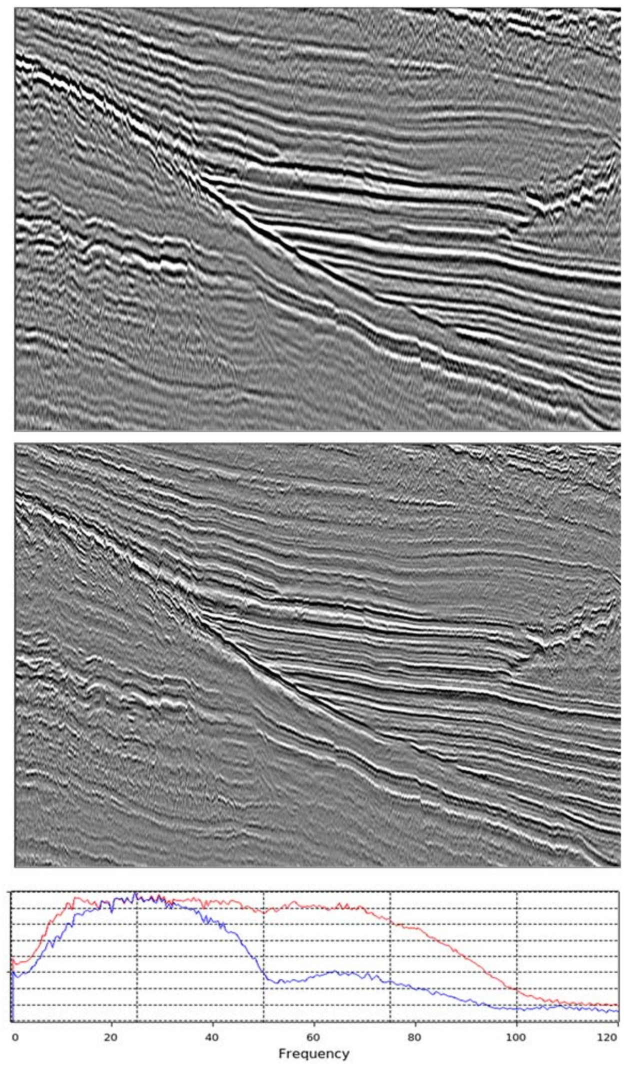

Figure 5 – Seismic sections before (upper) and after (lower) broadband processing. The spectra show the normal bandwidth data in blue and the broadband data in red.

One important feature of the CWT method is that it analyses the seismic to find the fundamental frequencies and then computes the harmonics and sub-harmonics from the reflected data. When the convolution-like process is used to add these frequencies back to the data, the input wavelet is reshaped, thus broadening the spectrum. Any harmonic and sub-harmonic frequencies that do not match the reflectivity in the input data will not be added, meaning that noise amplitudes are not enhanced at the same level as signal, resulting in a good signal-to-noise ratio in the enhanced low and high frequencies. The frequency enhancement is verifiable and consistent with geology.

With the addition of low and high frequencies to the data one can estimate the increase in vertical seismic resolution. Figure 5 shows a comparison of a zoomed in section of the conventionally processed data with a section of the broadband data. The increase in resolution is quite dramatic on the broadband data, where the resolution is up to five times higher, assuming an interval velocity of 3,500 m/s within the layers. In Figure 6 we identify a single reflector on the conventional data using a red arrow. The broadband data reveals more than one thin bed and a wedge feature which is not visible on the standard data set, also identified by a red arrow. The enhanced resolution allows for better definition of thin beds which can improve the accuracy of the stratigraphic interpretation. This improvement is made possible with the use of the broadband processed data.

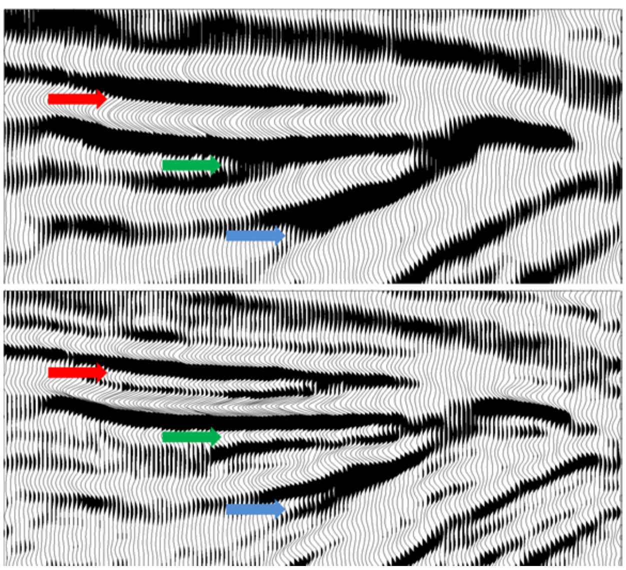

Figure 6 – Enhanced resolution on Sergipe 2014 Line 1330 before (upper) and after (lower) broadband processing.

Synthetic Seismogram Correlation

The synthetic well traces computed from the digital well logs and the corresponding seismic composite traces are used to calculate correlation coefficients for both the normal bandwidth and broadband seismic data. The additional reflectivity information contained in the broadband data is also represented in the higher frequency synthetic well traces generated with higher frequency wavelets. Normal bandwidth and broadband well-seismic ties and correlation plots are shown in Figure 7. The resolved events attributable to an increase in seismic bandwidth are highly correlatable between the well synthetic and the extracted composite seismic trace from the well location. We suggest this strong correlation proves that the additional information in the broadband seismic data is representative of real geology. The cross correlation plots also demonstrate that the peak to trough ratio, indicative of the relative size of the side lobes, is significantly improved. In addition the length of the wavelet is noticeably decreased as a result of the broadband processing.

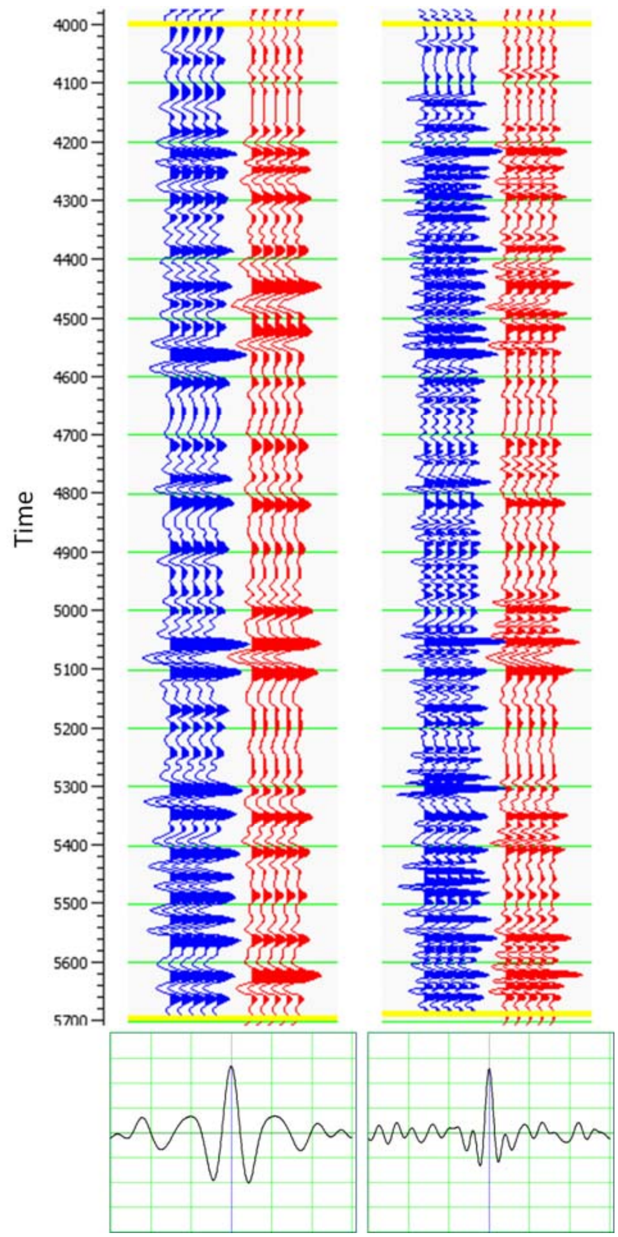

Figure 7 – Well-seismic correlations for normal bandwidth and broadband data. The synthetic traces calculated from the well logs are in blue, and the composite seismic traces are in red. The bottom plots show the correlation between the well and the seismic data. The left track shows the normal bandwidth, and the right plot shows the broadband data.

Sequence Stratigraphy

A sequence stratigraphic interpretation was done on seismic data located near the Barra well on both the normal bandwidth and broadband data sets. A seismic line from the 2014 Sergipe seismic survey approximately 1 km from the Barra discovery well was used. The data was processed through PSTM and PSDM, including a de-ghosting and bandwidth extension work flow as described earlier. Figure 8 shows a zoomed in portion of the line with a comparison between the PSDM converted to time with and without broadband and de-ghosting. The figure shows that with the broadband data, more detailed interpretation and mapping are possible due to the improved resolution of the data. A top and base of the sand layer can be interpreted on both data sets. However, the higher dominant frequency of the broadband data allows for a more accurate definition of the location and thickness of this layer. Upon tying the well data to the seismic, the top and base of the upper Cretaceous sand (Maastrichtian in age) are detectable on the higher frequency broadband display at 5.030 seconds and 5.050 seconds, respectively. The increase in frequencies on both the low and high ends and the corrected ghost notches in the spectrum allow for clearer definition of thin beds in and around the target zone. Additionally, improvements can be made in the regional geologic interpretation.

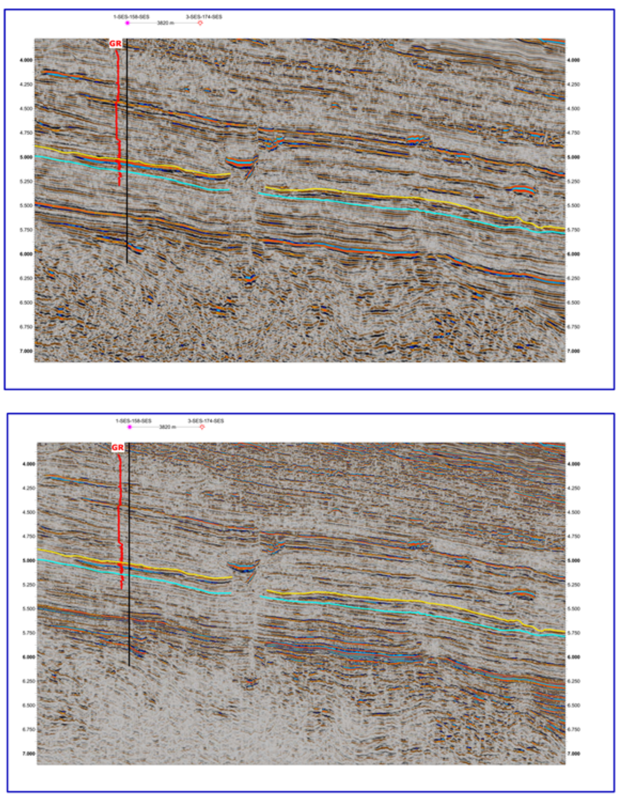

Figure 8: Conventional pre-stack depth migration converted to time (top) and broadband pre-stack depth migration converted to time (bottom) with sequence stratigraphic interpretation and gamma ray log for Barra 1-SES-158 well.

After close investigation, it was determined that the slope fan system down-dip from the well correlates with the sand zone at the well. The fan system is interpreted to be located from approximately 6.4 km from the well out to around 20 km from the well (proceeding to the southeast). Within the fan, the conventional data has two primary peak and trough pairs of reflectors. However, the broadband data has more variations in reflectivity within this zone, revealing more internal geologic architecture. It is possible to interpret sand bodies from the higher frequency trough-peak pairs within the fan system. As is typical with a slope fan system, the sand is not continuous as it flows in a channel down the slope and is deposited. This subtle characteristic is visible and interpretable on the broadband seismic data, though not on the conventional data.

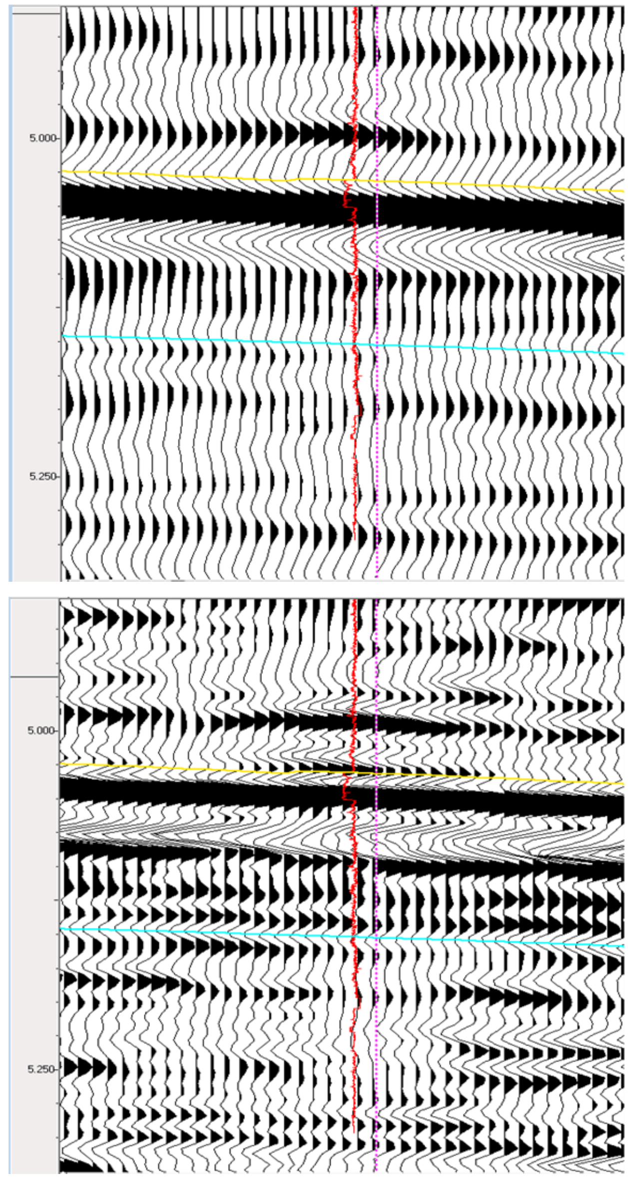

Figure 9: Zoom of conventional PSDM (top) and broadband PSDM (bottom) both converted to time with gamma ray log and sequence stratigraphic interpretation.

Conclusions

The Sergipe basin is a clastic sedimentary depositional environment with compressional (i.e. depth of burial) seismic velocities. Typical ¼ wavelength tuning thicknesses at the reservoir level are 40 to 50 m at conventional seismic frequencies. These tuning thicknesses may be larger than typical reservoirs found in the Sergipe Basin.

We demonstrate that a processing methodology using the Continuous Wavelet Transform can increase the seismic bandwidth substantially, such that the depth resolution can be improved from 50 m to 10 m. We contrast conventional analysis using the Fourier transform with the CWT. We show that the Fourier transform, with its assumption of a stationary input time series is not well-suited to the analysis of both local (i.e. reservoir) and global information. As a consequence of its non-stationary input assumption, we show that the CWT is well-suited for the simultaneous analysis of both local information and global information. We illustrate significant improvements attributable to broadband processing in stratigraphic interpretability for an on-lap feature.

We use a synthetic seismogram computed from a conventional, limited bandwidth wavelet and compare it to a synthetic seismogram computed with a broadband wavelet. We compare these synthetic seismograms to composite seismic traces from a line that ties the Barra discovery well, and use correlation coefficients to quantify the improvement in resolution attributable to broadband processing.

By increasing the seismic bandwidth by one or more octaves using the continuous wavelet transform for de-ghosting and bandwidth enhancement, we demonstrate the ability to resolve stratigraphic sequences that are thinner than the reservoir found in the Barra discovery well.

Acknowledgments

The authors wish to thank our colleagues at Spectrum and Geotrace for their valuable input and contributions. In particular we wish to acknowledge Joel Latchman and Amy Peterson at Geotrace for their tireless work ethic, and Dan Negri for his valuable geologic insight. We also wish to thank management at Spectrum for permission to publish this paper.

References

Saunders, M., Geiger, L., Negri, D., Stein, J., Sansal, A., and Springman, J. (2015), Improved stratigraphic interpretation using broadband processing – Sergipe Basin, Brazil. First Break, March, 2015

Yu, G., Shan, N., and Robinson, M. (2012), Resolution improvement and stratigraphic interpretation for the thin turbiditic sands in offshore Sabah, Malaysia – A pilot study, SEG…

Hellman, K., Stein, J. A. and Shah, N., [2014] Marine Deghosting using the Continuous Wavelet Transform, Second EAGE/SBGF Workshop, Rio de Janeiro.

Stein, J.A. [2014] HDBand™: Noise Cancelling Headphones for Your Seismic Data, *World Oil, September 2104, 35.*

Smith, M., Perry, G., Stein, J., Bertrand, A., Yu, G. [2008] Extending seismic bandwidth using the continuous wavelet transform: First Break, 26, 97-102.

Brookes, D., McCann, D. and Armentrout, D. [2014] Interactions Between Deghosting and Other Processing Steps - Searching for the Optimal Processing Order. *2nd EAGE.SBGf Workshop 2014, Broadband Seismic*, Extended Abstracts, C05

Sablon, R., Russier, D., Hardouin, D., Gratacos, B., Soubaras, R. and Lin, D. [2012] Multiples Attenuation for Variable-depth Streamer Data, Shallow and Deep Water Cases. *74th EAGE Conference & Exhibition*, Expanded Abstracts. Y011

Saunders, M., Negri, D., Ross, C, and Bowman, S. [2014] Sergipe Basin, Brazil: Direct Hydrocarbon Indicators from Calibrated AVO Stacks. GeoExpro

Melton, B. (2008) A Geological and Geophysical Study of the Sergipe-Alagoas Basin