Bringing New Clarity to the Campos Basin Using Broadband and TTI Imaging: A Case Study

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Abstract

The Campos Basin, offshore Brazil, has generated significant exploration interest after several discoveries, most recently the Pão de Açúcar well in 2012. The basin is entirely covered with 2D data, and in addition modern 3D data has been acquired over some areas.

In this paper, we present images from the Olho de Boi 3D survey acquired from November 2013 to March 2014. The better quality of the new images available in this area will significantly improve the understanding of the petroleum system. This paper will discuss key technologies applied to the processing of the 3D survey:

1) Broadband acquisition and processing: slant cable acquisition and fully deghosted solution in tau-theta domain (source and receiver de-ghosting)
2) Tilted-Transverse Isotropic (TTI) model building and imaging

Finally, we compare the 3D PSDM to 2D PSDM lines with conventional pre-processing. Broadband 3D acquisition and processing combined with imaging algorithms like TTI Kirchhoff, TTI RTM PSDM and Delayed Imaging Time (DIT) scans bring new clarity to the presalt and post salt sections.

Introduction

The Brazilian presalt trend spans the Santos, Campos, and Espírito Santo sedimentary basins. These basins are centered along the continental shelf of the Brazilian Atlantic margin and formed as a result of rifting during the early Cretaceous that ultimately opened the South Atlantic. The basins accumulated considerable volumes of primarily lacustrine sediments, which developed into prolific source rocks and reservoirs of the Lagoa Feia petroleum system. These presalt source rocks are believed responsible for most of the oil discovered to date in Brazil.

The Pão de Açúcar well in the Campos Basin (Figure 1) found a presalt hydrocarbon column of 500 m, one of the thickest to date in Brazil. The Pão de Açúcar well is the third discovery in BM-C-33 block after Seat and Gávea. Numerous presalt discoveries dating from 2008 and including the Pão de Açúcar attest the significant potential of the Campos Basin presalt, which is emerging as a prolific hydrocarbon fairway similar to the Santos Basin.

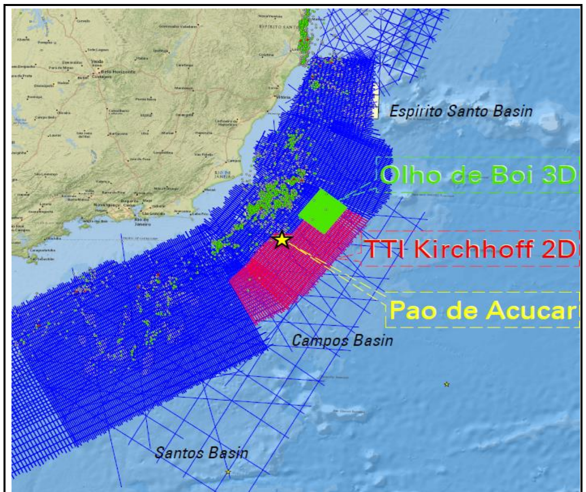

Figure 1: Campos Basin, offshore Brazil

Imaging of the presalt events is a key element in determining the continuity of the Lagoa Feia petroleum system. Improved velocity models can provide more accuracy at the base of salt and better definition of the presalt section. Resolution is important for estimating reservoir thickness, due to the potential for depositional thinning of the presalt section over basement highs.

In this paper, we discuss the processing of the 3D survey. In an effort to achieve better imaging and resolution, the survey was acquired with a slant cable (~ 10 m depth at the near offset and ~ 25 m depth at the far offset of 8100 m streamer length) and a processing-based broadband technique was applied. A low cut filter and shot ordered noise attenuation were performed followed by de-bubbling the data. At this stage deghosting was performed for receiver and source. The deghosting was followed by a zero phase application, cold water statics, shot and channel amplitude corrections plus a 3D surface multiple model estimation with adaptive subtraction (TAME). Before radon was applied several final denoise steps were done using different ensemble sorts. Then radon was applied before and after PSTM, and finally post-stack processing after datum corrections.

TTI model building and imaging were applied to the data. Other important factors in improving the velocity model were the application of grid-based tomography to update the postsalt section, layer-constrained tomography between the top of the Albian and the top of salt to update the Albian layer, Kirchhoff and RTM PSDM algorithms to build the salt model and tomography and Delayed Imaging Time (DIT) scans to update the presalt section.

Broadband processing

The data was originally filtered using a 2 Hz filter to preserve as much low frequency signal as possible prior to deghosting. Noise due to swell or spikes in the data were removed using a Time-Frequency comparison of amplitude in given frequency bands and adjacent time windows, with each frequency band having a time window based on frequency range of the starting data set. The data had significant bubble energy across all offsets. We use an operator designed from all offsets to remove the undesirable low frequency of the bubble energy prior to attempting the broadening of the spectrum through source and receiver deghosting. This allows for a more accurate result of the deghosting effects during the test phase.

For an accurate ghost estimation the data cannot be zero-phase before deghost. The primary reflection is the leading 'trough' of the wavelet and would be 'rotated' with zero-phase giving an inaccurate result if done before hand. The ghost energy in marine data is caused by extra reflections off the sea surface both immediately after the gun is fired and an extra reflection of the propagated wave off the surface near the receiver, and a combination of both contribute to a third ghost. This affects the data resolution by producing three extra 'legs' for each event, and affects the data in frequency when the surface reflections cancel with the primary reflections. The variation from different reflection angles off the sea surface waves, the angle of reflection surfaces, and angles due to depth variations of reflection surfaces have to be considered in order to remove the ghost effectively. For a flat streamer, the apparent time delay between the main signal and its ghost is dependent on the angle of the propagation. This is true as well for a linear slanted cable. For this dataset, we applied a processing-based solution as described by Masoomzadeh, et al., 2013. With a slanted cable configuration we use a Tau-Theta transform which when transformed gives the ghost a regular distance in the transform which can be predictably subtracted with a direct relationship between the angle of the cable and the angle of reflection ($2\alpha = \Delta\theta$, where α is the cable angle, and θ is the angle of reflection). (Figure 2)

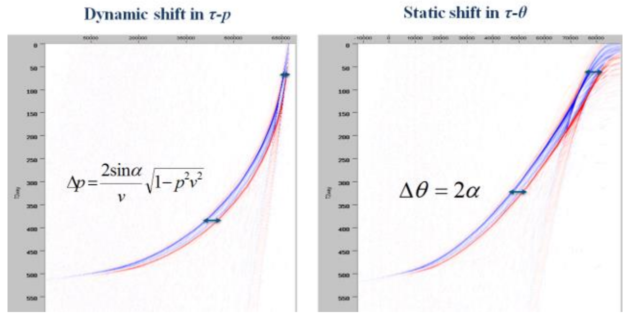

Figure 2: Transforms; *Tau-P* (right), *Tau-Theta* (left)

For the receiver side the receiver depth measurements are used to determine the approximate notch frequency for each channel after the data has been transformed in the *Tau-Theta* domain. The geometry of the cable is calculated and then used to estimate the lateral offset of the ghost energy in the *Tau-Theta* domain. Then an operator is calculated for each shot and applied. For the source side ghost, a search is performed for frequency dependent free surface reflection coefficients, typically for low, mid, and high reflection coefficients. After this, the deghosting operator is applied in the *Tau-P* domain complemented by a statistical stage which includes a carefully designed deconvolution operation, averaging over a large number of common-slowness traces in order to address the remaining residual ghost. We can see after source and receiver deghosting that the notches have been greatly reduced and the frequency spectrum follows a natural decay before phase correction. (Figure 3)

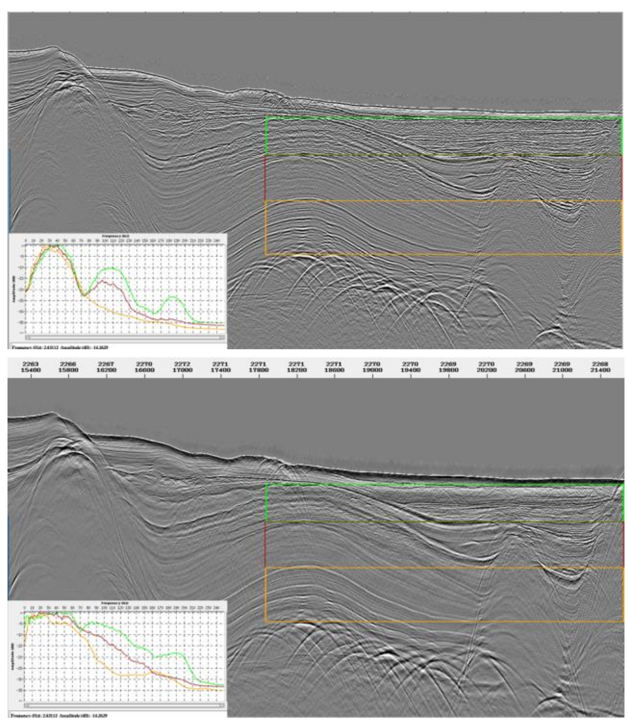

Figure 3: Stack from Campos Basin Before (Top) and After De-Ghosting (Bottom).

Depth Imaging

Improving the overall image, and in particular the presalt structures, is key for exploration success. The complex overburden, thick salt, and salt layer heterogeneity are an additional challenge in the Campos basin. Due to the presence of minibasins with steeply dipping events and other complexities, the PSDM velocity model is designed as a TTI model. Kirchhoff and RTM imaging are combined to define the salt model.

The TTI model building process starts with previous 2D sediment PSDM velocities converted to a 3D cube and calibrated to check shots. From a post-stack depth migration volume the dips are first scanned and smoothed to define the predominant dip, and then the axes of symmetry, which are assumed to be perpendicular to the bedding, are derived. A two-step anisotropic model building approach was carried out. Using focusing analysis (FAN) (Cai, et al., 2009 and He et al., 2009), epsilon and delta are analyzed at check shot locations. FAN involves constructing the true focusing operator by demigration of a common image gather back to the time domain, then calculating the focusing operator for different values of epsilon and delta from the focal point (zero offset image), and searching for the minimum objective function (the difference between the true focusing operator and the calculated focusing operators). Epsilon and delta were estimated at well locations and then propagated along geologic horizons.

The velocity model was refined with 3 passes of structure conformed tomography above the top of salt or top of the Albian when present. The Albian layer was updated with an additional pass of tomography constrained between the top of the Albian layer and the top of the salt.

After the sediment model was updated, TTI Kirchhoff with turning waves and TTI RTM were used to define the top of salt. The salt model was built in a top down approach, alternating sediment flood and salt flood migrations. Kirchhoff migration is efficient and provides high-resolution images that are very good for top of salt interpretation. However, overhangs and multiple salt bodies in close proximity can make ray-tracing difficult so RTM is also used. RTM is a wave-equation based algorithm with no high-frequency approximation; it is capable of handling multipathing, meaning it can image areas with sharp velocity contrasts. Also, RTM better images event termination against steeply dipping salt flanks, which helps to define salt boundaries. The combination of TTI Kirchhoff with turning waves and TTI RTM provide a better toolbox for achieving a more accurate salt interpretation.

The presalt model was updated using tomography and DIT scans (Wang et al., 2009). DIT scans based on Reverse Time Migration are an effective technique for updating the velocity model in areas of low signal-to-noise (S/N). When the incorrect velocity is used for migration, the energy is focused at the zero offset with a non-zero time imaging condition. Generating positive and negative non-zero time imaging conditions produces data that emulate imaging with variable velocities. The DIT images are sorted to gathers and conditioned; then semblances are generated. The semblances are automatically picked as described by Wang et al., (2011). The DIT picks are converted to residual velocities and the velocity model is updated. For quality control purposes, composite images are formed by selecting the DIT panels that produce the best focused and coherent images.

Figure 4 shows an RTM PSDM image overlaying the final velocity model. Note the velocity model conforming to the structures and the high velocity Albian layer.

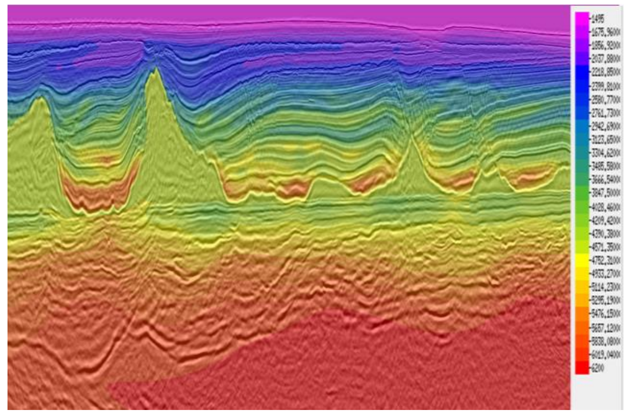

Figure 4: TTI RTM overlaying the velocity model. The presalt events exhibit good continuity

Results

Figure 5 shows a salt body imaged with Kirchhoff PSDM and broadband processing. The removal of the ghost leads to recovering the low frequency content of the signal, consequently suppressing the side lobe and sharpening the images, which are beneficial for achieving accurate interpretation in general, and in particular for better definition of the top and base of the salt. Broadband processing also improves resolution of faulted areas in the shallow section.

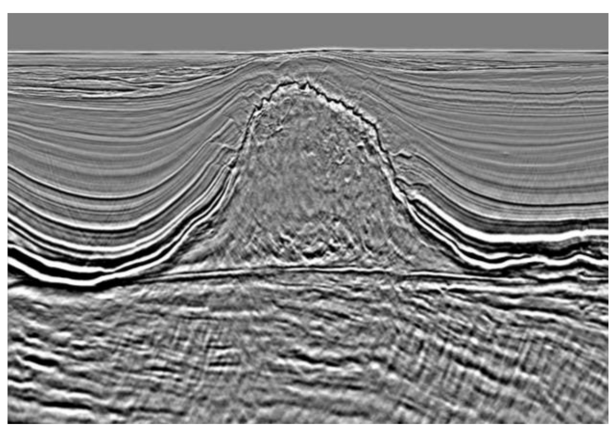

Figure 5: Broadband TTI Kirchhoff PSDM. Note the clear fault definition and sharp the top of salt.

The results were also compared to 2D PSDM images processed with conventional processing (Figure 6). The events are accurately placed and the challenges generated by out of the plane energy typical in 2D data processing are largely overcome. The well-defined salt bodies lead to better continuity of the presalt events.

TTI Imaging has improved steeply dipping salt flanks and sediments in the minibasins.

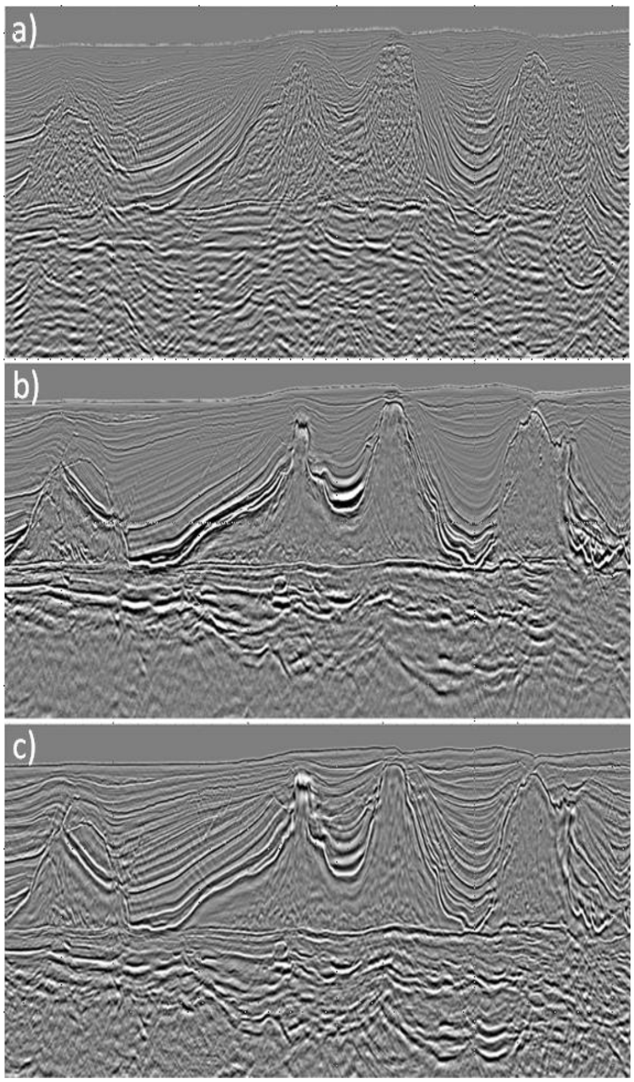

Figure 6: a) 2D TTI Kirchhoff PSDM (image courtesy of the WesternGeco/TGS Brazil 2D Data Alliance); b) 3D Broadband TTI Kirchfoff PSDM (no gain) and c) TTI RTM (35 Hz)

Steeply dipping reflectors (SDRs) below salt are clearly imaged by use of TTI model building and TTI RTM. Accurate mapping of SDRs can increase understanding of the evolution of the tectonic model. Figure 7 shows the better resolution and continuity of the presalt events and SDRs.

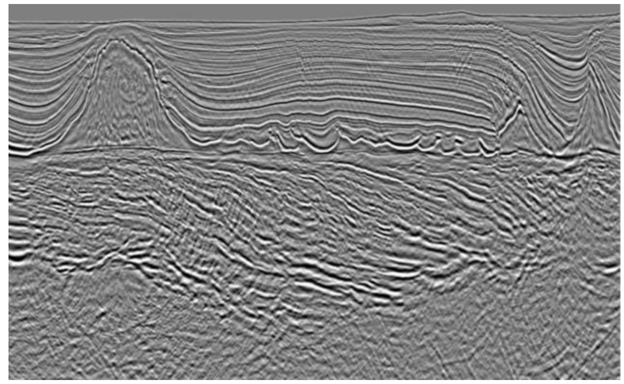

Figure 7: TTI RTM (35 Hz). Note the steeply dipping reflectors (SDRs)

Conclusions

Imaging with 2D data, particularly below salt, is not optimal due to the scattering of the wavefield. Use of modern 3D, particularly broadband, data can significantly reduce risk when imaging presalt events. The application of broadband processing combined with TTI model building and imaging of 3D data can significantly improve the quality of the images available in the Campos Basin and increase understating of the presalt petroleum system and tectonic model.

Acknowledgments

The authors would like to thank Daniel Chaikin, James Keay, Gloria Cheng, Sampad Laha and Landis Newbanks for their contributions; Connie VanSchuyver for reviewing the manuscript; and TGS for permission to publish this paper.

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