Improved reservoir imaging and understanding with Dual-Sensor Streamer in deep-water Santos Basin

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Abstract

Over the last few years, starting with the introduction of the dual-sensor towed streamer technology in 2007, new acquisition methods and technologies have been made available by providing broader seismic frequency bandwidth. The prime objective is to deliver better imaging to enable improved reservoir understanding without any compromise in pre-stack data quality and acquisition efficiency. The key element here is: how can we have a seismic acquisition system, processing and analytical workflow that broadens the frequency content of the data while increasing the signal content (signal-to-noise) and at the same time delivers an improvement in the reservoir understanding and the reservoir properties estimation using the full pre-stack seismic data without any trade off?

In this paper, we will present some recent analysis/results obtained in the deep-water Santos Basin using the dual-sensor streamer technology. We will examine its effectiveness and benefits by comparing the results to already impressive imaging data from an adjacent recent conventional seismic dataset. The view will not be necessarily to look only at the results from an imaging point of view but also to look at them from a reservoir perspective. Thus, the focus will be on demonstrating the value of such a broadband dataset from the point of view of an end user reservoir geoscientist or development/production geophysicist.

Introduction

The most obvious benefits of broadband seismic techniques relate to the increase in resolution on offer from the wider bandwidth, and the improved penetration due to signals richer in lower frequencies. The arguments for broadband are so compelling that there is good reason to believe that all new acquisition will be broadband before too long.

What is perhaps less well known and less publicized, are applications aside from pure imaging, where broadband data has a significant impact on the reliable prediction of reservoir properties. The benefits are significant, as highlighted by the case study presented in this article.

Deriving physical rock properties or having a better reservoir understanding from the seismic data offers great value to geoscientists. After all, it is rocks that operators are drilling, not acoustic signals. Pre-stack seismic inversion in combination with rock physics analysis is the most common workflow to derive elastic properties and subsequently rock properties from a combination of seismic data and well information. One fundamental aspect of all inversion methods is that a particular seismic data set can lead to a range of inversion results. With narrow band seismic data there can be a lack of information on the high side and/or low side of the amplitude spectrum, so geoscientists tend to constrain the number of possible solutions to reach the most reliable one. Normally, this is done by incorporating a background low frequency trend model based on known or a-priori information, usually using nearby well log data or other geological values. As a consequence, the uncertainty of the results away from these constraints, i.e. away from well control, increases significantly. Using broadband seismic data, with its extended frequency content, substantially reduces the amount and bias of a priori data input – thus, we can rely more on the 3D information content from seismic data away from well control. Recorded broadband data thereby makes the inversion or any quantitative interpretation solution less dependent on what we already believe, and increases its usefulness in areas where a-priori information may be scarce or uncertain. In other words, the entire process is more data-driven than model-driven.

Method

The ghost in marine seismic recording is the result of an almost perfect reflection of the acoustic wave-field from the sea surface. Up-going waves are reflected back as down-going waves with a reversed polarity, and interfere constructively for certain frequencies and destructively for other frequencies. This phenomenon occurs both on the source side and on the receiver side. The affected frequencies depend solely on source and receiver depths. Conventional marine seismic acquisition therefore involves a trade-off between the various frequency ranges. To record high frequencies, sources and receivers have to be towed shallow, which strongly attenuates low frequencies. Conversely, a deep tow favors low frequencies at the expense of high frequencies.

A dual-sensor streamer, with co-located pressure and motion sensors, has been developed (Carlson et al., 2007). Such a streamer effectively removes the receiver ghost while maintaining the efficiency of towed streamer acquisition. This acquisition system enables an extension of seismic bandwidth at both the low and high ends of the frequency spectrum and has been used extensively in 2D and 3D mode over many regions and basins across the world and in the present case in the Santos deep-water basin offshore Brazil.

The broader bandwidth achieved by the removal of the receiver ghost (Söllner, 2007) has crucial advantages at both ends of the frequency spectrum and more recently, a de-ghosting approach has also been developed for the source side. By having a time and depth distributed source the new design has allowed the removal of the source ghost (Parkes et al., 2011 and Parkes and Hegna, 2011). Eliminating both the source and receiver ghosts increases even more dramatically the seismic bandwidth which has a significant impact on the seismic image as well as on the precision and fidelity of elastic properties. This in turn enables improved understanding and characterization of the reservoir.

It has been demonstrated recently that recording and preserving more low and high frequencies across the seismic section presents significant advantages for reservoir properties estimation. For instance, recording and preserving more low frequency seismic signal means that less a-priori information is required as input for a low frequency model used for absolute inversion, which significantly increases the reliability of elastic properties prediction based on more seismic data away from well control (Reiser et al., 2012).

Case study within the deep-water Santos Basin

The BM-S-50/52 Phase 2 dataset is a MultiClient 3D seismic survey on trend and/or adjacent to some prolific discoveries in the northern Santos Basin, including Merluza, Lagosta, Cedro and Mexilhao (Figure 1). This survey, acquired in late 2012, bridges a gap in pre-existing 3D coverage in an area with light oil to condensate/gas prospectivity attracting substantial industry attention at various reservoir potential level: post and sub-salt. The present survey is designed to help support a more complete understanding of the local and regional geological setting. The primary reservoirs in the aforementioned discoveries are deep marine turbidite sandstones within the Ilha Bela Mbr of the Itajai-Acu Fm.

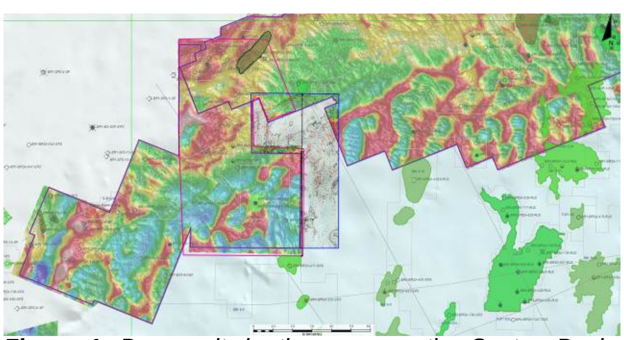

***Figure 1**: Base salt depth map over the Santos Basin. The blue rectangle represents the location of the BM-S-50/52 Phase 2 survey acquired in 2012, comprising close to 2,350 sqkm of pre-stack depth migrated data*

Over this dataset, PGS is currently performing time and state-of-the-art pre-stack depth processing aimed at enabling clearer imaging focused on the pre-salt interval. A significant effort is made to build an accurate velocity model for the depth migration and the broader bandwidth of the dual-sensor is helping in this regard.

Pre-stack analysis is still in progress, but even at this early stage, when compared with an adjacent modern conventional seismic data set in this deep-water Santos Basin environment, the uplift is evident in terms of:

a) Improved penetration and imaging of deep targets, especially at the pre-salt level
b) Better signal to noise, especially of deeper sub-salt targets,
c) Broader seismic frequency bandwidth, especially at the low end, and,
d) Improved fidelity of pre-stack elastic attributes.

The 2012 dual-sensor broadband survey abuts a modern 2008 survey acquired with conventional solid streamer to the west (Figure 2). The surveys have a narrow overlap zone of 2km which allows direct comparison of the two surveys, and allow the assertions of improved imaging and data quality arising from dual-sensor broadband data to be validated.

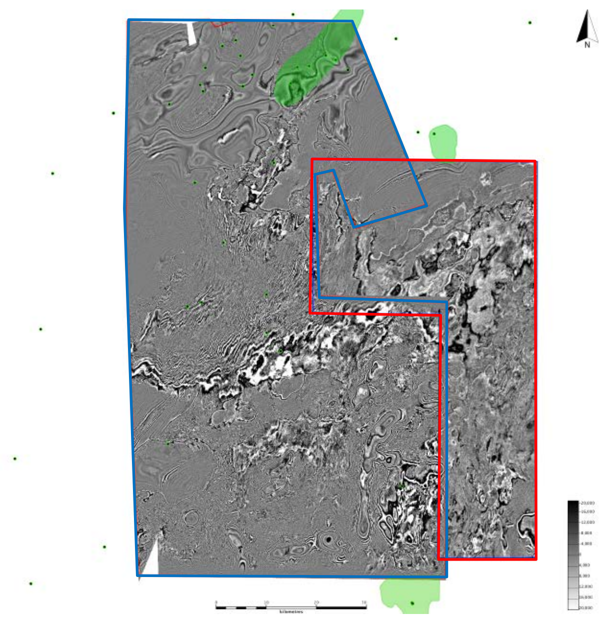

Figure 2: Deep depth slices (6500m) intersecting the pre-salt section showing the conventional survey (left) and dual-sensor broadband survey (inverted L-shape, with blue outline on the right), with an overlap zone where comparative analysis was performed

Figures 3 and 4 show the full stack Kirchhoff PSDM depth images for the same line location from the conventional and dual-sensor broadband surveys.

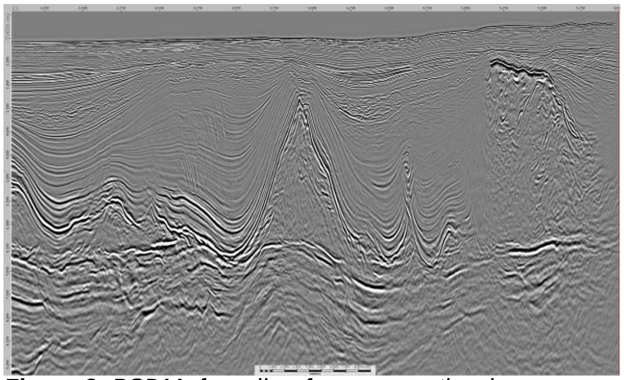

***Figure 3**: PSDM for a line from conventional survey co-located in the overlap zone, orientated south to north.*

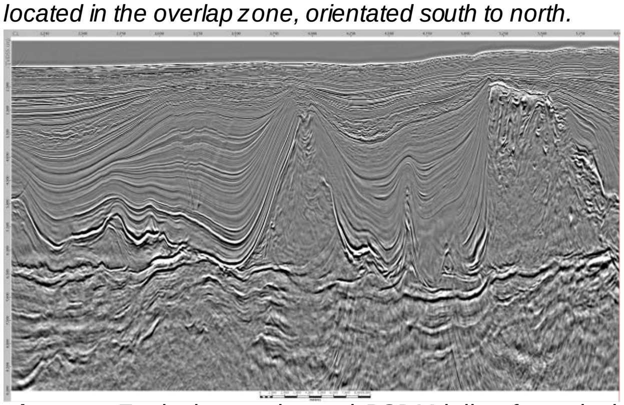

***Figure 4**: Equivalent co-located PSDM inline from dual-sensor broadband survey in the overlap zone*

The improvement in recorded and preserved bandwidth, particularly at deeper target depths, is evident by visually comparing these lines. Also it can be noticed that the top and the base of the salt is sharper, crisper and cleaner due mainly to the increased bandwidth on the low and high side. This increase of frequencies significantly reduces the amount of side lobe energy on the wavelet (Reiser et al., 2012) which has the benefit of enabling a sharper definition of the top and base of any geological unit with greatly reduced interference from wavelet side lobes.

The amplitude spectra for a deep panel (5.5-6.5 seconds TWT) from this line are illustrated in Figure 5.

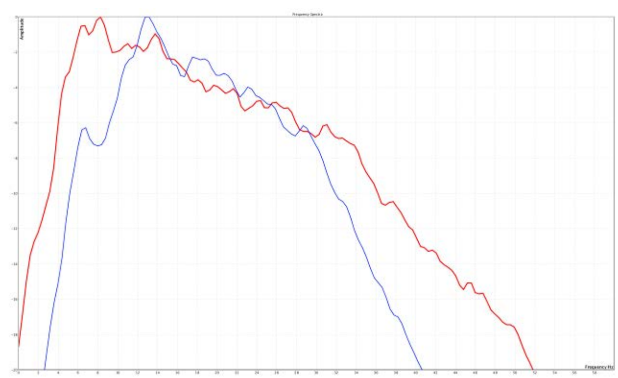

***Figure 5**: Amplitude spectra in dB comparing the mid angle stacks for the conventional (blue) with dual-sensor broadband (red) for a deep window below base of salt.*

The above figures clearly demonstrate that even analyzing deep in the section (around 5.5 to 6.5 sec), at the level of sub-salt targets, the range of the low frequencies is significantly extended with the dual-sensor streamer data compared to the conventional data across all offset/angles without the detriment of losing any high frequencies.

The combination of the deep streamer tow (15m) and the co-located dual sensors (vertical particle velocity sensor and hydrophone) significantly increases the recording of the low and the high frequencies across the whole seismic section. At the pre-salt interval, the dual-sensor data shows over an octave of additional low frequencies. It is the additional low frequencies and improved signal to noise penetrating deeper that enable potentially better elastic attributes (work still on-going at the time of the abstract) to be derived in the sub-salt objectives.

For the conventional and dual-sensor datasets, a relative pre-stack inversion has been performed (Figure 6 and 7).

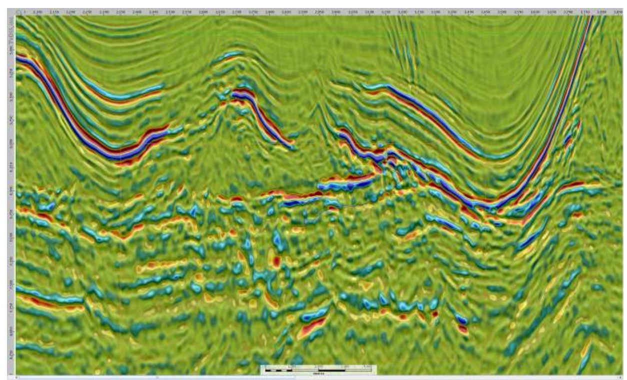

***Figure 6:** Depth panel from relative acoustic impedance (from a pre-stack inversion workflow) of conventional survey co-located in the overlap zone focusing on the resolution of sub-salt targets*

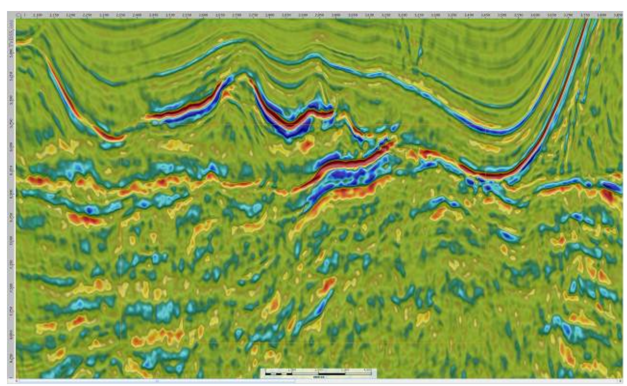

***Figure 7:** Depth panel from relative acoustic impedance (from a pre-stack inversion workflow) of dual-sensor broadband data for the same location as in Figure 6*

Work is still on-going, but even on provisional quick-look, it can be clearly observed that the relative acoustic impedance on the dual-sensor seismic data is significantly less noisy. In the pre-salt section, the inversion of the broadband data provides a clearer, less noisy structural image as well as cleaner definition of lithological variation within sub-salt layers. This provide a more reliable information for reservoir characterization, mapping and correlation of geological events in the pre-rift, syn-rift and sag phases.

The amplitude spectra of relative acoustic impedance for both conventional and dual sensor data can be compared (Figure 8).

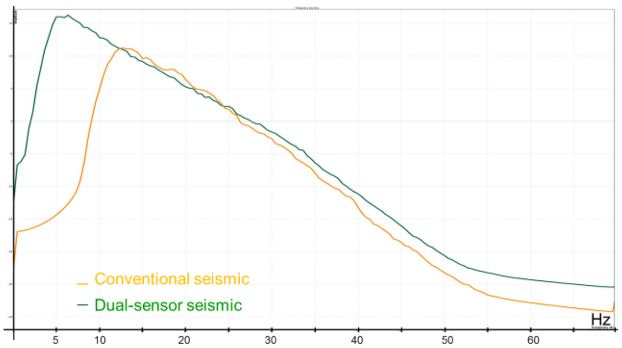

Figure 8: *The above figure represents the relative acoustic impedance amplitude spectra for the conventional seismic (in orange) and the dual-sensor streamer data (in green).*

The dual-sensor relative seismic impedance spectra clearly exhibit significantly more low frequencies and more high frequencies than the conventional seismic. The frequency gap between the 0Hz to the frequency of the dual-sensor is in the order of 3Hz which is small compared to the industry norm today. Relative acoustic impedance with more low frequencies will enable the estimation of absolute elastic properties with significantly less "a-priori" model required (work to be completed). The latter will increase our ability to estimate the reservoir properties more accurately away from well control. This will provide explorers and producers with a seismic or inversion product which, when it is calibrated to well information, can be used with a higher degree of confidence away from the well control. This represents a significant advantage in terms of prospect de-risking and reserve evaluation and in the confidence that can be attributed to reservoir delineation and characterization estimates.

Summary

Deeper penetration with improved signal-to-noise and broader bandwidth of dual-sensor data are shown to be:

- More interpretable: supra-salt lithologies, salt boundaries and pre-salt targets are cleaner and more readily interpreted, giving improved structural definition and lithology discrimination
- Deeper imaging: More low frequencies, with more signal recorded and preserved, enable better imaging of deep targets, for example tilted fault-blocks and syn-rift sediments beneath thick salt
- More precise: Broader bandwidth with improved signal-to-noise, has the potential to enable more stable elastic attributes (especially Is and Vp/Vs), which in turn allow derivation of more precise reservoir properties, and estimation of fluid and lithology distributions with more confidence
- More seismic-driven inversion: More than an octave of additional low frequency signal preserved in dual-sensor data means that the range of frequencies over which a low frequency model is required for absolute inversion is much reduced, and the seismic data has a greater contribution to the overall inversion result in data away from limited well control.

Conclusions

By comparing recent contiguous conventional and dual-sensor 3D seismic data from the deep-water Santos Basin, this paper demonstrates that the quieter, broader bandwidth enables improved resolution and quality of seismic imaging, especially of deeper and pre-salt targets. The more stable and precise elastic attributes derived from pre-stack dual-sensor volumes lead to potentially more accurate and reliable reservoir property prediction.

Encouraged by improved results like the one presented in this case example, broadband seismic is increasingly being demanded, for challenging areas where deep imaging and reliable reservoir delineation are essential. The technology also has additional benefits for 4D seismic repeatability. This is one of the first published 3D examples from the Brazilian deep-water producing basins, but many successful applications are expected in the challenging deep-water targets offshore Brazil in the future.

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