



## Multi-azimuth imaging for deep-water pre-salt reservoirs in Santos Basin, Brasil

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### Introduction

This paper presents a collaborative PETROBRAS-CGGVeritas project for optimizing the seismic image of Santos Basin pre-salt structures. For this study, 200 km<sup>2</sup> of the Lula field (ex Tupi) has been chosen as pilot area. The Lula field is one of the largest offshore oil field and is located at 250 kilometers off the coast of Rio de Janeiro. Inside the pilot area, the target reservoir lies below 2000 m of water, then 1000 m of sediments and 2000 m of salt. Because the Top Of Salt (TOS) presents a highly variable topology, we investigate how his geometry influences the illumination at the Base Of Salt level (BOS) and what are the consequences on the pre-salt reservoir seismic image. Due to the variability of the salt layer, different geometry and azimuth of acquisition may provide different amplitude seismic response at the pre-salt level.

By combining two existing datasets acquired with two different azimuths on the deep-offshore Lula field, we study and assess the benefits of multi-azimuth illumination for pre-salt carbonate reservoir imaging. The main objectives of this study are:

- Evaluate the uplift of multi-azimuth or wide-azimuth acquisitions for pre-salt imaging.
- Develop appropriate processing and imaging techniques for the pre-salt targets.

### Illumination study

Although advanced depth migration algorithms have already shown their potential for the pre-salt structural imaging, "true amplitude" imaging beneath salt bodies of complex geometry is still challenging because it requires a homogeneous target illumination. With existing narrow-azimuth datasets acquired on Lula field, lateral amplitude variation along the pre-salt events can be observed on the seismic image and seem not to be related to lithology changes. However, these narrow-azimuth datasets (named Tupi 30o and Cluster 90o) were acquired with 60o difference in azimuth. It offers a good opportunity for investigating the influence of different illumination patterns on the seismic amplitudes.

In a first phase, a qualitative illumination study was performed using a ray-tracing algorithm. Complex interfaces, such as the top of salt, are introduced in the

velocity model and illumination effects on the pre-salt target are analyzed using density maps of reflection points. The two datasets were modeled in respect of their acquisition orientation. Other acquisition parameters are kept identical for the synthetics in order to study the influence of the azimuth only. The study shows clearly the effect of the top of salt interface (TOS) on the pre-salt target illumination. The density maps at the base of salt level (BOS) show significant imprints of the highly variable TOS topography (Figure 1). These imprints are dependent on the two acquisition azimuths and on offset classes as well. The ray tracing illumination results show that an acquisition following the main TOS structures orientation produces strong laterally variable imprints, which are collocated throughout the offset classes. In this case, the full stack reinforces such spatially variable illumination. In contrast, an acquisition that crosses the main TOS structural orientation presents non collocated illumination patterns throughout the offset classes. Consequently, the full stack is more homogeneous. However, any amplitude pre-stack analysis will suffer on variable illumination within angle partial stacks. In the context of Santos Basin pre-salt reservoir, seismic surveys with a wide distribution of azimuths can potentially provide spatially homogenous illumination for the near, mid and far stacks.

In a second phase, we use of wave-equation modeling/imaging algorithm for studying accurately the salt layer effect on the pre-salt target illumination. The methodology consists in creating synthetic datasets based on a known velocity and reflectivity model, derived from an acoustic inversion of real dataset, with spatially continuous reflectivity value for the pre-salt horizon. Seismic datasets corresponding to three narrow azimuth acquisitions (named Tupi 30o, Cluster 90o and Diagonal 150o) and a wide azimuth acquisition (named WAZ) have been modeled and then migrated using a wave-equation based algorithm. For each case, the seismic response energy of the final images is compared with the (known) reflectivity model. The Wave equation approach confirms in a quantitative way the observation of the phase one. It can be noted that the methodology has the advantage of supplying illumination attribute for the entire seismic cube with an energy value directly related to the migrated data.

Obviously, the modeled WAZ dataset shows that seismic surveys with a wide distribution of azimuths provide the most homogenous illumination for stack images in the context of Santos Basin pre-salt reservoir (Figure 2). RMS maps, extracted from the "narrow azimuth" images at the base of salt level (BOS), show significant imprints linked to the highly variable top of salt (TOS) topography. The "Tupi 30o" acquisition produces the strongest laterally variable pattern in the final image directly correlated to the

top of salt topography. In addition, the study demonstrates an interesting point about MAZ acquisition; the combination of the two azimuths not oriented within the TOS structures (Cluster 90o and Diagonal 150o) presents a better illumination distribution than the merge of the three azimuthal acquisitions. Because the Tupi 30o illumination patterns are so significant, the addition of this third dataset reinforces the illumination variability.

### Real data, Bi-azimuthal imaging of the Lula field

The two marine streamer seismic surveys acquired in the Lula pilot area presents an azimuth difference of 60 degrees and different design. Their acquisition descriptions are as follow:

- “Lula”: 14 cables with 50m interval; 8,000m max. offset; azimuth 30°/210° N.
- “Cluster”: 6 cables with 150m interval; 6,000m max. offset; azimuth 90°/270°N.

Although the acquisition discrepancy, we hope to minimize the global illumination variability and increase the consistency of the final image by combining both datasets in a single processing sequence.

Some key processing steps have been specifically investigated for optimizing dataset integration, such as cold water statics correction, TTI velocity model building by joint tomography and post imaging data conditioning. The datasets have been processed as a multi-azimuth survey, with true 3D algorithms sharing a common velocity and anisotropy model.

The cold water static process compensates for water velocity variation during and between the surveys. The water velocity is determined for each sail lines using the curvature (along offsets) of the water bottom reflections. Then, the cross-line variations are compensated dynamically in order to harmonize 3D gathers prior to migration.

The TTI velocity model is built with a nonlinear joint tomography algorithm taking into account simultaneously picks of the two datasets (Montel et al., 2010). By using the two azimuths, the velocity and TTI anisotropy models are better constrained and allows us to increase the velocity model resolution. In consequence, seismic events are more focused on the seismic image, especially for the top of salt and for pre-salt structures (Figure 3).

The two dataset are migrated with the optimized TTI velocity model and the final seismic images are combined together using a geostatistic operator (automatic factorial co-kriging) in the frequency domain. The process

enhances the common seismic part of the two azimuthal cubes and attenuates non-consistent seismic signals, such as noise or internal multiple. The lateral amplitude variation at the reservoir level, observed previously on single azimuth data, is then better constrained using both dataset.

### Conclusions

The illumination study carried out in this pilot area clearly shows the benefit of imaging Santos Basin pre-salt structures with different azimuths. The modeling of three narrow azimuth acquisitions showed highly spatially variable illumination at the base of salt level. In consequence, any reservoir characterization attribute derived from pre-stack amplitude analysis will contain the imprints of the complex TOS if only one azimuth dataset is used.

By combining two existing datasets in a single processing sequence, we take advantage of having different azimuths of acquisition. Key processing methodologies were identified and optimized in order to get full advantage of the data integration, such as cold water statics correction for compensating variations in the water column, high-definition joint tomography (Guillaume et al., 2012) for building TTI velocity model optimized for both datasets and post-imaging data conditioning for improving the signal-to-noise ratio of the final stack image.

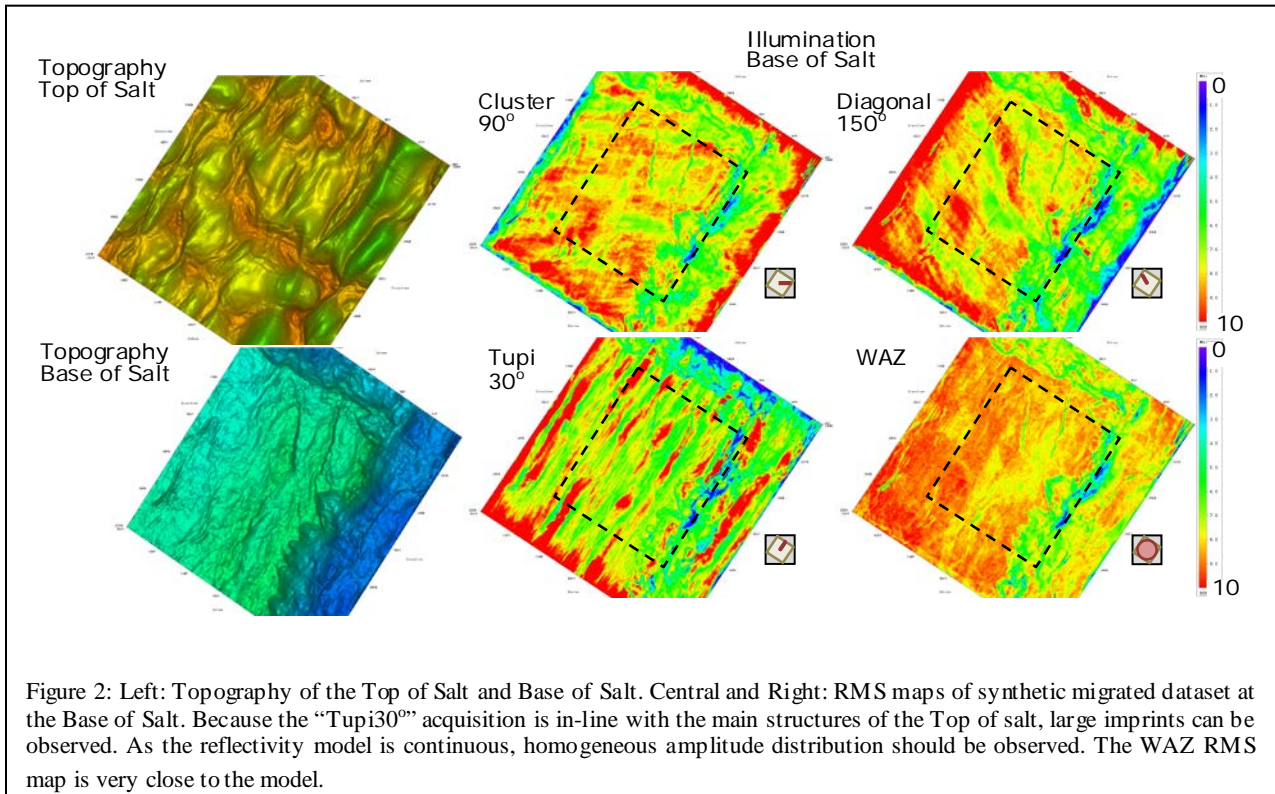
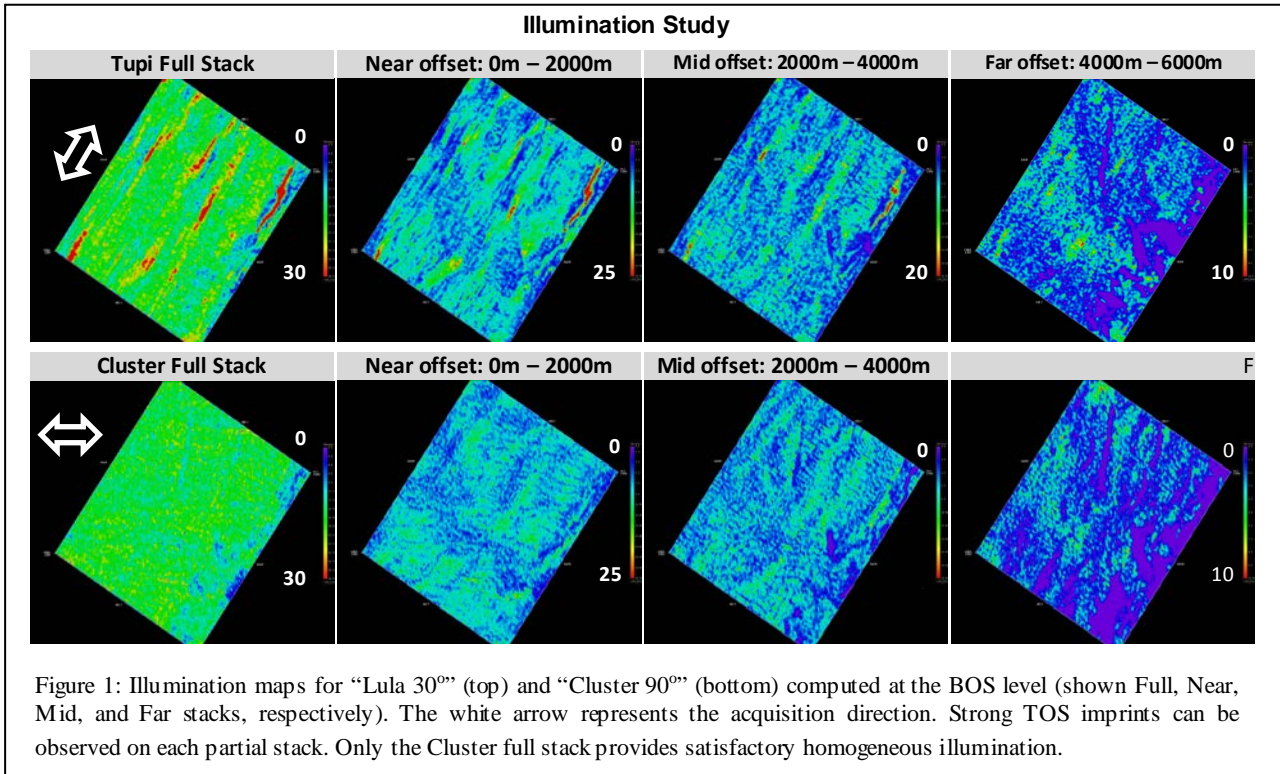
This “bi-azimuth” project provides a comprehensive assessment of the potential benefits of multi-azimuth data that will improve pre-salt carbonate reservoir imaging. The outcome of this evaluation will probably guide the decision of acquiring future WAZ data in Santos Basin.

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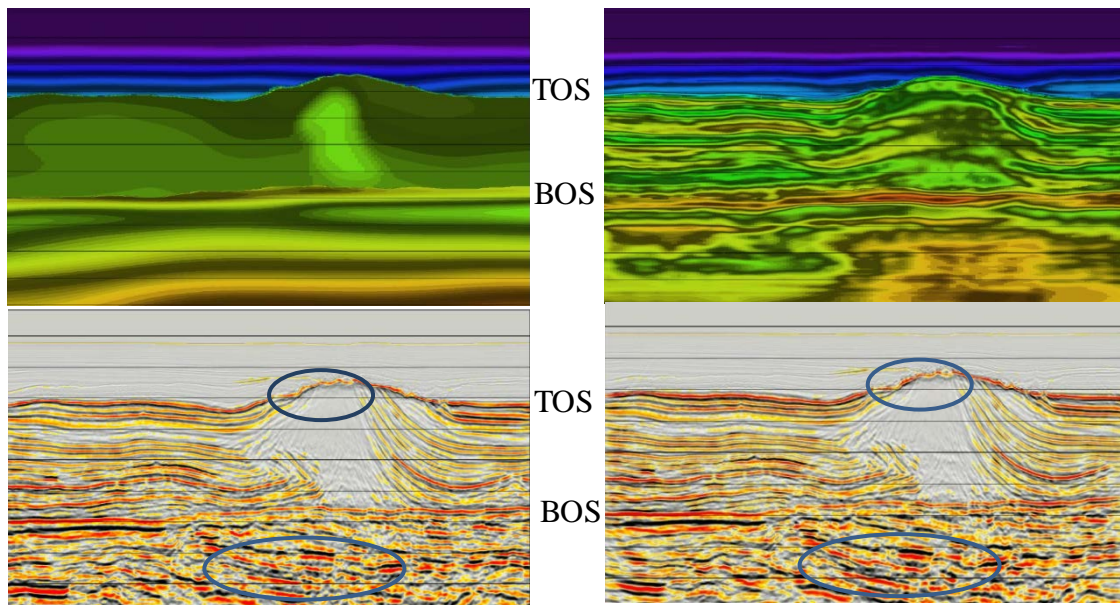


Figure 3: Velocity models and seismic images, before and after high-definition joint tomography. The tomography takes into account the picks of both datasets simultaneously. Better image focusing can be observed at TOS (top of salt) and below BOS (base of salt).