Squeezing out the presalt image from a narrow azimuth dataset in Brazil's Santos basin.

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Abstract

Brazil's Santos Basin holds more than half of all the country's reserves within presalt oil deposits. The challenges to access the fractured and ununiform carbonate reservoir are deep water, a variable reservoir thickness, stratified salt layer and igneous rocks present in the post, pre and salt intervals that obscure the image.

In this case study we show how we used a comprehensive signal processing, model building and imaging workflow, to overcome the challenges of imaging such a complex area, using a dataset acquired with a towed streamer narrow azimuth acquisition geometry. Achieving a robust image ready for quantitative interpretation.

Introduction

In 2018 the reprocessing of 1000 sqkm of seismic data, in the Santos basin started. This narrow azimuth (NAZ) towed streamer survey, was acquired in 2012 with an 8000 m maximum offset in a 2000 m water depth environment. The previous processing was done in 2015.

The main goal for the reprocessing was to obtain a better image of the presalt target but furthermore to have data ready for a quantitative interpretation.

To achieve this the workflow was designed to generate broadband data, with free surface and interbed multiples well attenuated and to build a high-resolution velocity model. The data were then migrated with this velocity model using a 45Hz pre stack Least Squares Reverse Time Migration (LS RTM) to generate the final image

Signal processing

To have a better understanding of the presalt target interval is important to have booth a clear image of the events and a good definition of the faults. To achieve this, the data should have a good low frequency content. Hence, adaptive deghosting (AD) was applied to the data (Zarkhidze et al., 2016). AD removed the notches in the spectra produced by the source and receiver ghosts, generating a broadband dataset.

The high reflexivity in the sediment-salt boundary combined with the variable salt geometry generates two challenges. The first one complex free surface multiples that interfere with the presalt events as shown in Figure 1. When using 3D Surface Related Multiple Elimination (3D SRME) techniques to model this complex geometry boundary with its steep dips, large apertures are required. However, the flatwater bottom in the area or the smooth salt bodies require only a small aperture in the 3D SRME model generation, using the highest aperture required for a complex salt body over the whole project would be an

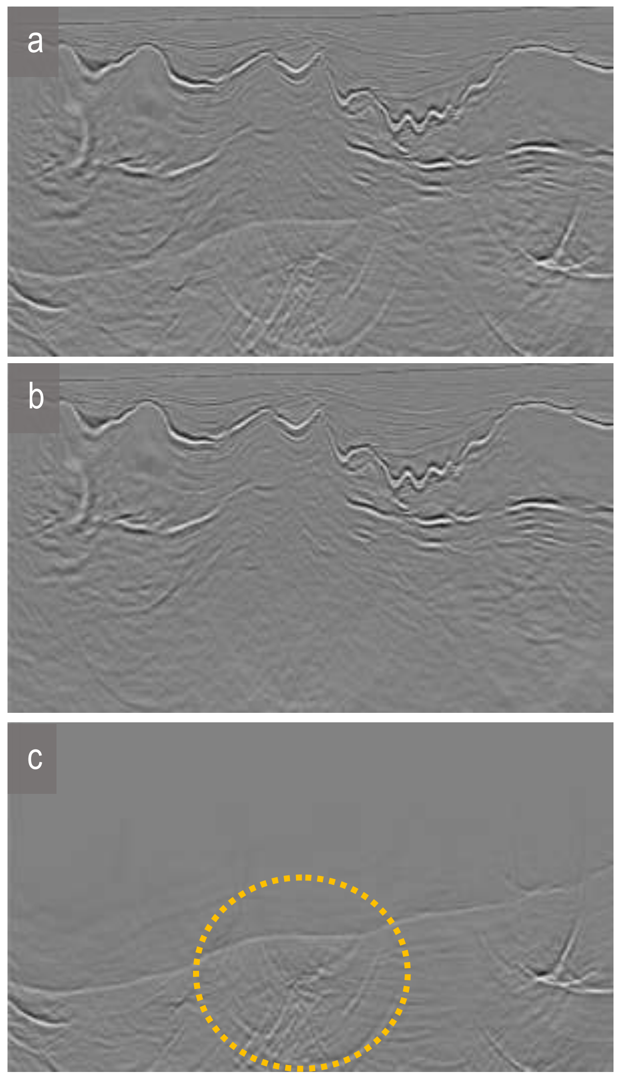

Figure 1: Variable aperture 3D SRME results. In a) migration before 3D SRME, in b) migration after 3D SRME has been applied and in c) difference between a) and b). Multiples generated from both the smooth water bottom and the more complex top of salt are both well attenuated.

inefficient approach. To improve this a variable aperture 3D SRME was used, considering the water bottom, top of salt and base of salt as the horizons to define the maximum aperture needed in the different areas of the project (Espinoza et al., 2017).

The second challenge related to the sediment-evaporite boundary is the generation of very strong interbed multiples which interfere at the target level. To attenuate them extended interbed multiple prediction (XIMP) was used (Melo et al., 2014). To account not just for the top of evaporites but for internal salt reflectivity produced by the anhydrite-halite boundary a layer approach was used instead of a horizon based. In this case eight models, correspondent to eight layers were generated.

To maintain data integrity without compromising the primary events the models were migrated and subtracted in the image domain.

Model building

The legacy model from the 2015 processing was the starting point for this earth model building project. Anisotropy was modified, to account for a compaction trend and made it zero in the postsalt igneous interval, while the velocity was scaled to compensate for the anisotropy changes and smoothed to remove the short wavelength details. This was the initial model for three

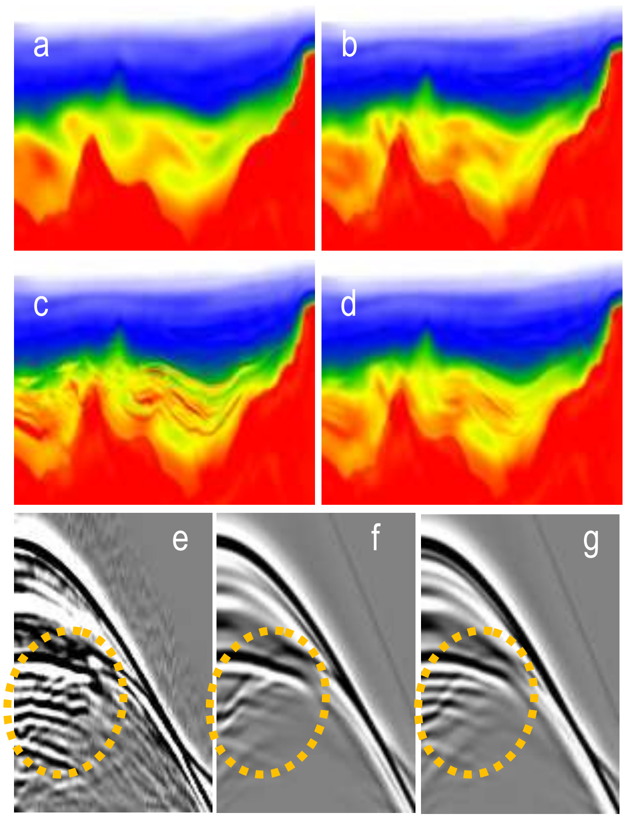

Figure 2: LS FWI with inversion constrain. a) FWI initial model. b) FWI result without including the constrain. c) The acoustic impedance resulted from inversion and converted to velocity, used as prior for FWI. d) FWI result with inversion constrain. e) An observed shot. f) Modeled with the FWI result without the constrain. g) Same shot modeled with the FWI model with constrain. It is clear how the more complex reflections get generated with the higher resolution model.

iterations of high-resolution common image point (CIP) tomography (Woodward et al., 2008) focused in the postsalt section. These were followed by Least Squares Full Waveform Inversion (LS FWI) to add resolution in the model. In the south east part of the project igneous bodies intercalated with sediment are present in the postsalt interval. To capture these small, high velocity bodies in the earth model a high-resolution velocity model was generated by using well-logs in the area to correlate between inverted acoustic impedance and velocity. This prior model, shown in Figure 2c, was then used within LS FWI to constrain the update, shown in Figure 2d, by simultaneously minimizing the mismatch between the observed and modeled data and the difference between

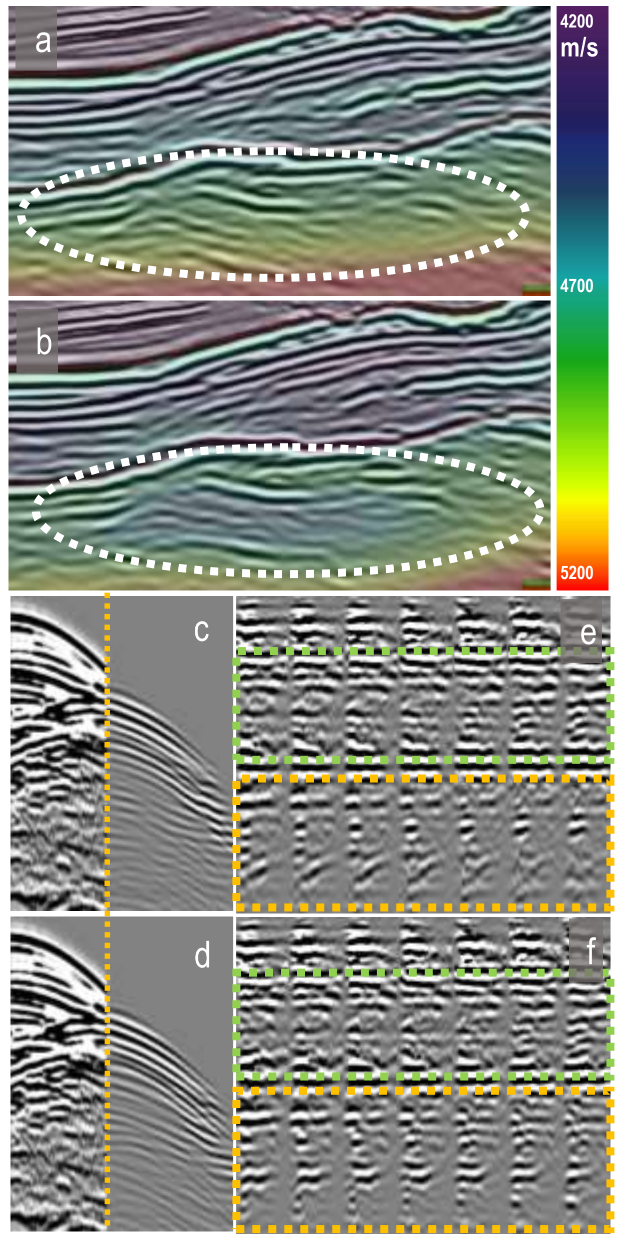

Figure 3: RFWI results, salt and presalt update. a) Initial model overlaid in RTM migration. b) A slowdown in the presalt velocities after RFWI results in a better focused image. c) Observed gathers in the left and modeled with the initial model in the right d) modeled gathers with the RFW velocities (right) has a better correlation with the observed one. In e) and f) migrated gathers before and after the update.

the resultant and prior models (Kang et al. 2019). As a comparison, the image in Figure 2b shows the LS FWI update with no such constraint while Figure 2(e-g) compare the observed and modeled shots. After LS FWI a final pass of high-resolution tomography was run to simultaneously update both velocity and epsilon in order to minimize the well mistie and residual moveout in the gathers.

Incorporating small overhangs in the top of salt interpretation in the more complex areas, helped in generating a more continuous base of salt image.

A general characteristic of Santos basin is the presence of anhydrite and halite in the evaporate sequence. This up to 700 m/s velocity difference between them needs to be incorporated in the earth model to correct imaging the base of salt and the presalt section.

Diving waves cannot penetrate beyond the top of salt with 8000 m cable length. To be able to update the salt and presalt Reflection FWI (Sun et al., 2016) was used. A smooth velocity generated based on sonic logs and long wavelength tomography was the starting point.

An intrasalt CIP tomography, with residual moveout picked in RTM subsurface angle azimuth gathers (SAAG) was used to bring more vertical resolution. The result was a smooth salt velocity field, that produced a more continuous and geologically plausible base of salt.

The base of salt was interpreted, and a smooth trend based in the legacy model was introduced in the presalt. The transition between salt and presalt was smoothed to allow for a combined update.

As mentioned, the interbed multiples interfere in the presalt image. To ensure a reflectivity absent of multiples, XIMP was applied to the input data to allow for a more stable Reflection FWI result.

A final CIP tomography iteration using RTM SAAGs was run before including the basement trend.

Results

To preserve the details at the presalt target level 45Hz RTM surface offset gathers (SOG) were produced.

The geological complexity in the area, such as variable stratigraphy within the salt and igneous rocks in different intervals combined with a NAZ acquisition resulted in amplitude variations at the presalt target, related to illumination. To compensate for these effects and broaden the data spectra LS RTM was performed in the prestack, image domain (Fletcher et al., 2012), enabling the data for more reliable prestack quantitative interpretation.

To perform the inversion, point spread functions (PSF) were generated for the 16 SOG of the RTM. These 3D wavelets capture the offset dependent, depth variable illumination as a function of dip and azimuth by imaging subsurface diffractors with the same migration algorithm, velocity model and acquisition geometry used to generate the RTM gathers.

Assuming the reflectivity is known, the seismic image could be generated by convolving the reflectivity series with the PSFs. In practice the PSF gathers are simultaneously deconvolved from the SOGs resulting in a reflectivity series.

Figure 4 shows the comparison between the RTM and LS RTM in the presalt interval. Illumination compensation and amplitude balancing near the base of salt is highlighted in the bottom RMS maps of Figure 4 taken both before (left) and after LS RTM (right). It should be mentioned that in the areas of severe illumination issues, such as regions with extensive igneous rock layers, the acquired data may often reach its limit. Here, LS RTM will improve the amplitude recovery with depth, but with limited uplift in comparison to less complex locations. For further improvement in the image another type of acquisition is often needed.

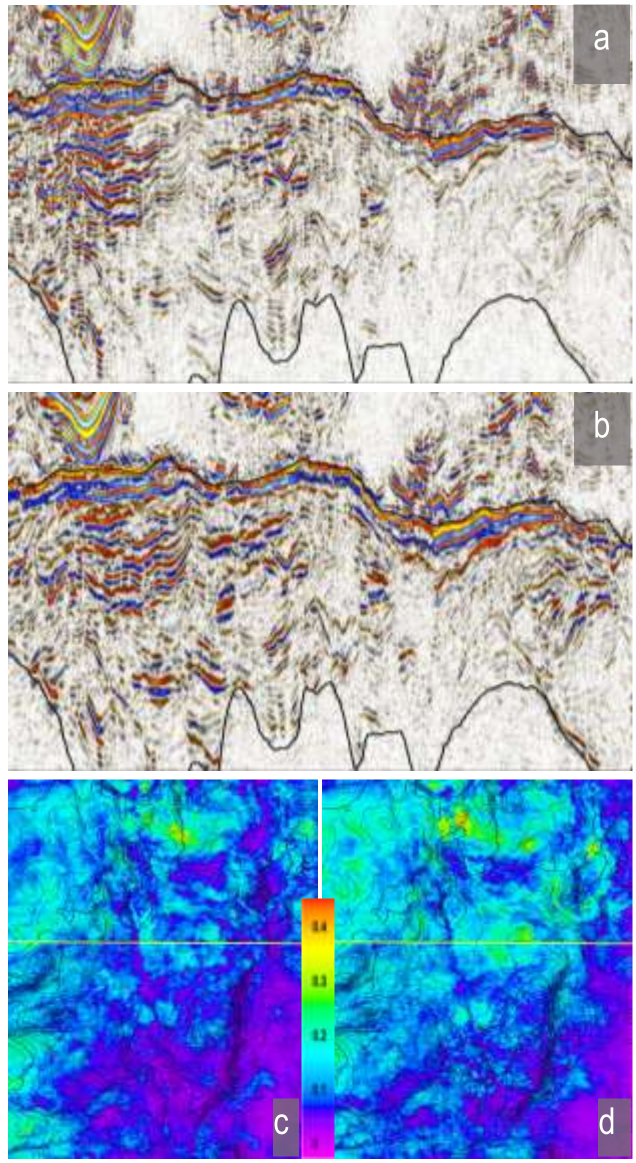

Figure 4: Better fault definition and amplitude compensation as a result of LS RTM. a) RTM and b) LS RTM. The illumination compensation can be observed in the RMS amplitude maps calculated between base of salt +100m and the basement before c) and after LS RTM d).

Conclusions

In areas of geological complexity where there is no other data than NAZ there is still work that can be done to retrieve more information from the data. Firstly, applying a robust signal processing sequence that generates a broadband dataset with AD, attenuates both, the free surface and interbed multiples with 3D SRME and XIMP. Secondly, using an earth model building that solves for the different challenges with the appropriate technologies, like tomography, least-squares and reflection FWI. Thirdly combining the signal processing and earth model building using appropriate imaging algorithms. Figure 5 shows how by doing this a clearer target image, with more reliable amplitude and frequency content can be achieved as shown.

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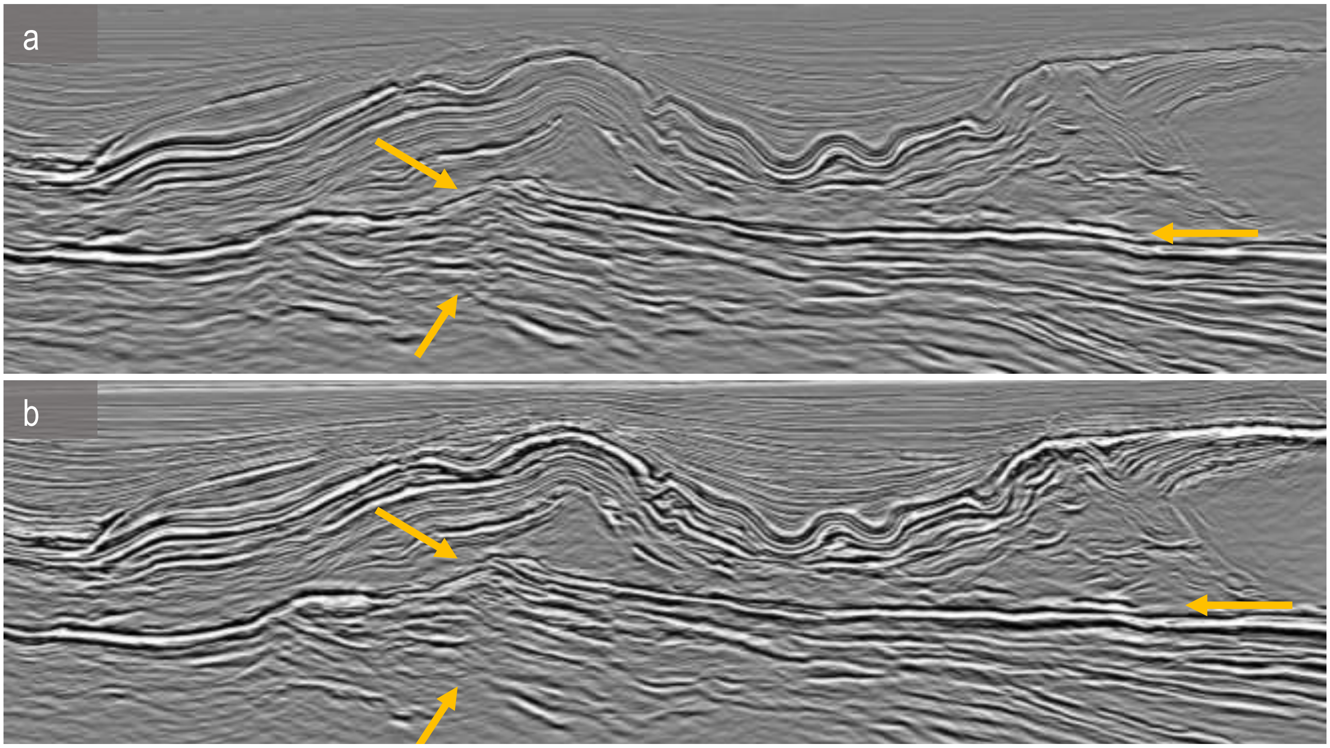

Figure 5: Comparison between a) Legacy image and b) final LS RTM result. Looking at the presalt target a much clear image with more continuous horizons can be observed in the right side of the image, bellow a simpler base of salt. Where the high in the base of salt is, the structure is better imaged, and the horizons better defined in the reprocessed image.