Internal multiple attenuation for four pre-salt fields in the Santos Basin, Brazil

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Summary

The Santos basin is known to contain strong internal multiples that pose a major challenge for the imaging of pre-salt reservoirs. Artifacts generated by incorrectly imaged internal multiples can affect model building and interpretation, and ultimately contaminate amplitudes in the pre-salt reservoirs. We examine four different pre-salt fields from the Santos basin, present our prediction and subtraction strategy, and detail our observations and learnings for each one of the fields in the context of internal multiples.

Introduction

The Santos basin, offshore Brazil, is well known for its giant pre-salt oil fields. While the common geological element of the Santos basin is the presence of a thick salt layer, other geological features of the basin can be quite varied. In the south-western and central parts, the occurrence of stratified salt is very common. Stratified salt is formed due to the variation of the amount of water and its salinity during the deposition period. In deeper water areas, due to the action of compression forces, there is formation of diapirs and the presence of allocthonous salt. Moreover, volcanic rocks are commonly found in the north-eastern part of the basin (Meisling et al., 2001).

Strong imaging artifacts generated by internal multiples have been previously identified in seismic data from the Santos basin (Hembd et al., 2011; Cypriano et al., 2015). Water bottom, top of salt, stratified salt, top of albian, top of cretaceous, and volcanic rocks are all potential generators of strong internal multiples in this basin. At each field, internal multiples have particular characteristics and implications for seismic imaging. Some multiples directly interfere with the reservoir image, affecting interpretation and AVO explicitly. Other multiples may be misinterpreted as primaries, thus causing errors in velocity estimation. The attenuation of internal multiples is therefore important for maximizing the value of the seismic product.

To honor the internal multiple differences throughout the basin, we need a robust data-driven internal multiple attenuation (IMA) method that can capture these multiples without explicit definitions of generators or stringent prior information. We used a method for predicting internal multiples proposed by Van der Neut and Wapenaar (2016) and implemented in Pereira et al. (2018). Subtraction was performed in the image domain using 3D curvelet filters (Wu and Hung, 2015; Ying et al., 2005).

We applied the proposed IMA flow to four fields of the Santos basin (Figure 1) and highlight our observations and learnings for each. All the datasets shown here are 3D narrow-azimuth towed-streamer surveys.

Internal multiple prediction and subtraction strategy

The proposed internal multiple prediction method (Van der Neut and Wapenaar, 2016; Pereira et al., 2018) is based on a crosscorrelation followed by a convolution of the data, similar to Jakubowicz (1998). The main difference is in the way the data is selected, and this defines which set of multiples is being predicted. The method relies on a separation of the data between an overburden region and a target region. The overburden region is defined to contain the internal multiple generators, and the target region is where the multiples are imaged (see Figure 2). The horizon separating these two regions can be quite arbitrary. No explicit or strict definition of generators is required. The implementation is shot-based and suitable for large 3D applications. All of these properties satisfy our requirements for IMA in the varied geological scenarios of the Santos basin.

To be consistent with the geology of the Santos basin, where there is an overburden with many strong impedance contrasts above the pre-salt layer, we used a horizon defined just below the top of salt (TOS). This choice of the overburden enabled us to predict the dominant internal multiples in each of the studied fields.

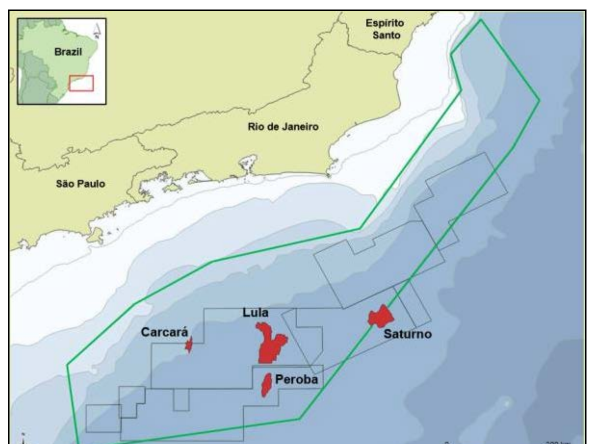

Figure 1: Map of the South-east Brazilian coast presenting the pre-salt polygon (green), seismic survey areas (gray) and the four analyzed pre-salt reservoirs (red).

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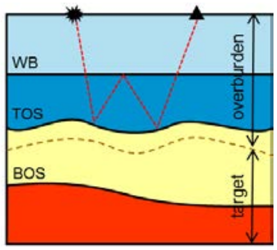

Figure 2: Typical geological configuration in the Santos basin. An example of an internal multiple is shown in red. A choice of horizon separating overburden/target areas is shown in brown.

Once the dominant multiples are predicted, we may also use additional horizons/models to identify sub-dominant multiples.

Data preparation included denoise, designature, deghosting, and surface-related multiple attenuation (SRME). Similar to SRME (Dragoset et al., 2010), data must be properly interpolated and the near offsets reconstructed to ensure a good prediction.

After the internal multiple model prediction, we moved to the subtraction, which can be very challenging due to the similarity of these multiples with primaries, in terms of amplitude, frequency, apparent dips, etc. We performed the subtraction post-imaging on offset cubes using a method based on the 3D curvelet transform (Wu and Hung, 2015; Ying et al., 2005). The curvelet-based subtraction has the advantage of minimizing the damage to the primary events, thanks to the intrinsic decomposition of the input data and the multiple model into different dip and frequency bands. Moreover, the use of the 3D transform honors the 3D nature of seismic data.

Peroba and Lula

These two reservoirs are both large oil fields in the central part of the Santos basin. This area is characterized by strong impedance contrasts within the stratified salt. Similar to most areas within the Santos basin, we observed that the water bottom and top of salt generate the most dominant internal multiples. These multiples typically have a relatively long period. Moreover, a notable amount of short period internal multiples are generated by the stratified salt layer and the top of salt reflector. To address both kinds of multiples, we used two horizons to predict different models. The first horizon falls just below the top of salt, predicting dominant longer period multiples. The second horizon lies just above the base of salt (BOS), predicting shorter period sub-dominant multiples. Both models were then subtracted simultaneously. The extra effort in this strategy can be particularly beneficial for the Lula and Peroba fields since both kinds of internal multiples often generate imaging artifacts at the depth of the pre-salt reservoirs (see Figure 3a and Figure 4a).

Looking first at Peroba, after 3D curvelet subtraction, it is possible to better interpret the reservoir structures and to observe a cleaner definition of the base of salt (Figure 3b). Improvement on the gathers can be observed as well. Figure 3c-e show the results of IMA on a depth slice at 5800 m depth.

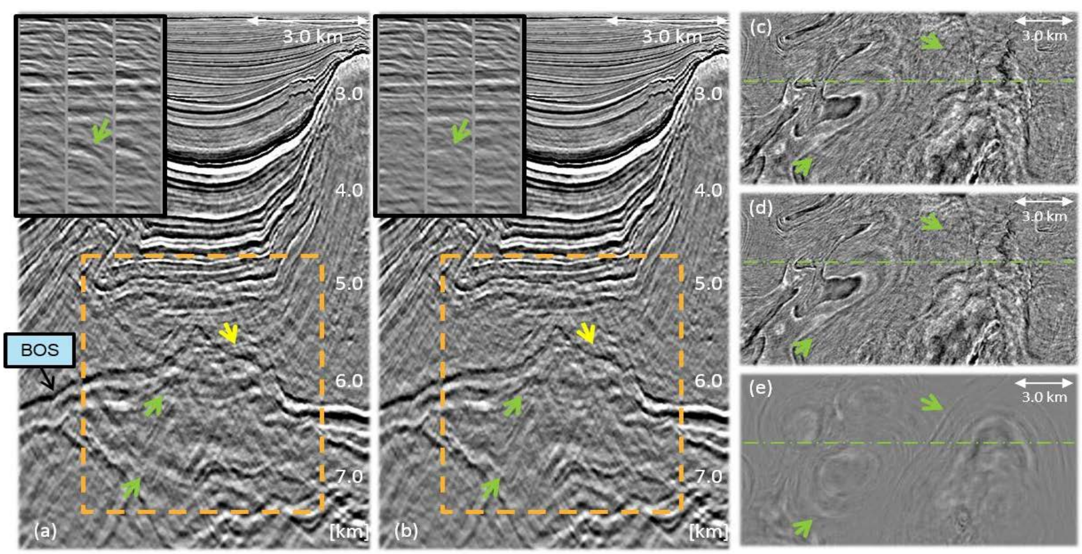

Figure 3: Results of internal multiple attenuation on the Peroba field: (a) and (b) inline section from the near offset cube before and after IMA; (c) to (e) depth slice before, after IMA, and difference. Green dashed line indicates position of inline section, green arrows indicate dominant longer-period internal multiples and yellow arrows indicate weaker shorter-period multiples.

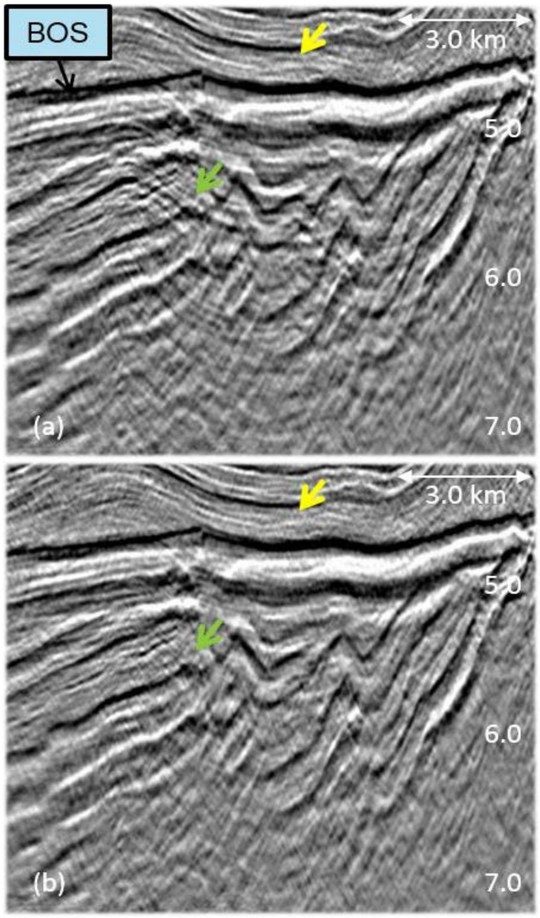

Figure 4: Results on Lula field showing a zoom on the pre-salt region; (a) and (b) inline section of near offset cube before and after internal multiple attenuation. After IMA, pre-salt events are better defined and more easily interpreted. Green and yellow arrows point to long and short period multiples respectively.

The results of internal multiple attenuation in the Lula field are shown in Figure 4. After the subtraction, it is possible to clearly identify the pre-salt features, allowing for more correct interpretation and reservoir characterization. Overall, IMA improves the reliability of reservoir imaging in these fields.

Carcará

This field lies in the shallower-water central part of the Santos basin (Figure 1). It is characterized by a relatively shallow and flat top of salt, as well as stratified salt. The multiple pointed to in Figure 5a is generated by the top of salt and the water bottom. For predicting the multiple model, we used only the TOS horizon. Most of the strong internal multiples of this field are imaged within the stratified salt. These multiples do not have direct impact on reservoir characterization, and when using an accurate velocity model, they can be easily spotted within the stratified salt. However, they can affect velocity model building during early stages of intra-salt tomography. A strong internal multiple, such as the one shown in Figure 5, can be mistakenly picked for the residual move-out correction (RMO), which may result in errors in intra-salt velocity estimations, thus deteriorating the image at the base of salt and pre-salt.

In this context, the application of IMA has the potential to improve the robustness of the velocity update through a better preconditioning of the data prior to tomography.

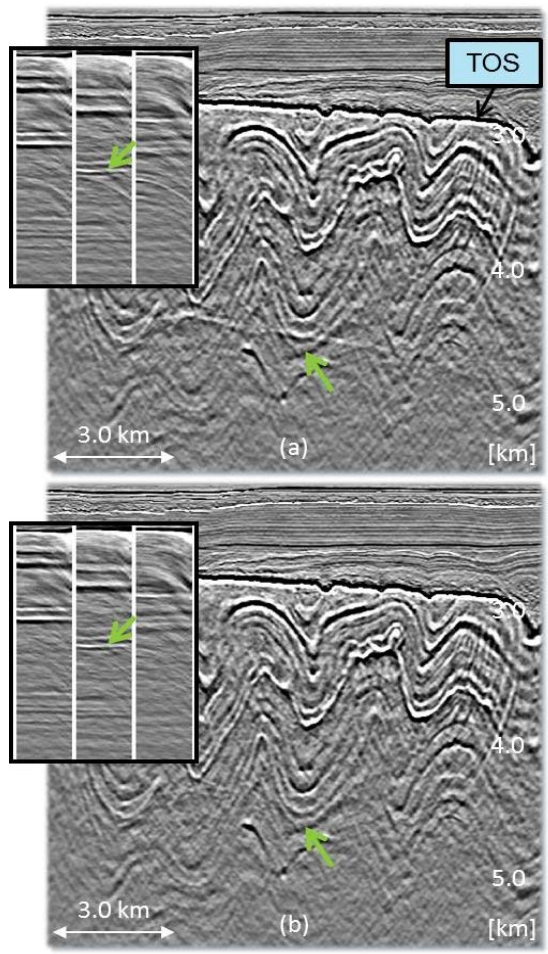

Figure 5: Results of internal multiple attenuation inside the salt layer in the Carcará field for near offset cube; before (a) and after (b) IMA. The gathers highlighted in top-left side of each image show an event that could mislead the RMO picking, leading to incorrect velocity updates. The event is no longer visible after IMA.

Saturno

Lately there has been increased interest in imaging ultra-deep reflectors and mapping of the basement layer. Deep reflectors can be used in "basin modeling" to gain better understanding of field evolution, thus enabling more reliable prospect identification. This is particularly important for new exploration areas such as Saturno, with the first 3D seismic data set acquired in 2017.

The Saturno field lies in the deeper part of the Santos basin towards the edge of the pre-salt polygon. It is surrounded by deep volcanic layers that can generate strong internal multiples. Figure 6a shows an example of a deep internal multiple, below 8 km depth, generated by the volcanic layer above. This multiple could be misinterpreted as a real event, but the multiple model (Figure 6c) confirmed that it is an internal multiple and can be reliably subtracted (Figure 6b). The horizon used to guide the modeling is again the TOS.

If not identified correctly as internal multiples, this type of event can be interpreted as part of the basement or deep sediments, which may lead to misinformed basin modeling and increased risk associated with prospect identification.

Conclusions

We have studied the behavior of internal multiples for four different fields inside the Santos basin. Internal multiples in each of the fields affect the data differently and can have direct or indirect implications for reservoir imaging.

The proposed prediction method has been shown to give robust internal multiple predictions for all of the fields, and the 3D subtraction strategy in the migrated domain performed well in these different geological scenarios.

It should be noted that subtraction of internal multiples remains challenging because move-out, frequency content, and amplitude behavior of internal multiples are very close to that of primaries. The use of a multi-dimensional subtraction strategy minimizes primary leakage. We also believe that, in the context of internal multiples, more efforts should be dedicated to improving the multiple model through, for example, a better interpolation of the input data. This can improve the amplitude and phase behavior of the predicted model and ultimately have a positive impact on the success of the subtraction.

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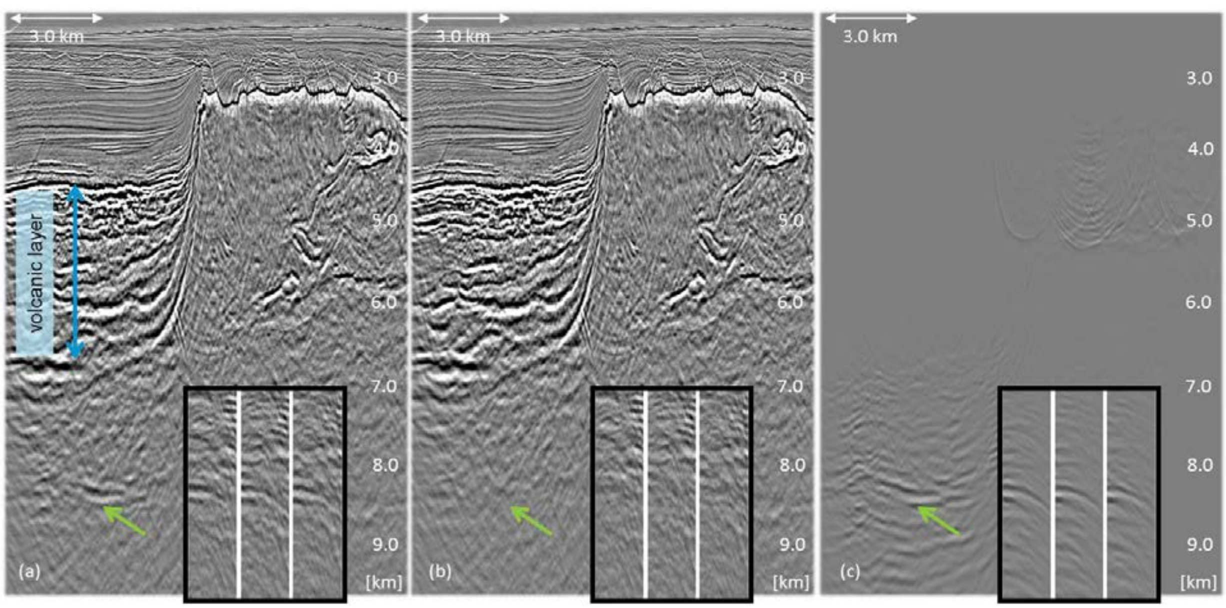

Figure 6: Example of an internal multiple in the deep region of the Saturno field below a thick volcanic layer: (a) and (b) inline section from near offset cube before and after subtraction; (c) predicted model. The strong deep event, also observed in the gathers view (inset), is successfully removed after IMA; the new image can avoid unrealistic interpretations and provide more reliable analysis.

10.1190/segam2018-2990024.1

REFERENCES

Cypriano, L., F. Marpeau, R. Brasil, G. Welter, H. Prigent, H. Douma, M. Velasques, J. Boechat, P. de Carvalho, C. Guerra, and C. Theodoro, 2015, The impact of inter-bed multiple attenuation on the imaging of pre-salt targets in the Santos basin off-shore Brazil: 77th Conference & Exhibition, EAGE, Extended Abstracts, N114–06, https://doi.org/10.3997/2214-4609.201412691.

Dragoset, B., E. Verschuur, I. Moore, and R. Bisley, 2010, A perspective on 3D surface-related multiple elimination: Geophysics, **75**, no. 5, 75A245–75A261, https://doi.org/10.1190/1.3475413.

Hembd, J., M. Griffiths, C. Ting, and N. Chazalnoel, 2011, Application of 3D interbed multiple attenuation in the Santos Basin, Brazil: 73rd Conference and Exhibition, EAGE, Extended Abstracts, H047, https://doi.org/10.1190/sbgf2011-350.

Jakubowicz, H., 1998, Wave equation prediction and removal of interbed multiples: 68th Annual International Meeting, SEG, Expanded Abstracts, 1527–1530, https://doi.org/10.1190/1.1820204.

Meisling, K. E., P. R. Cobbold, and V. S. Mount, 2001, Segmentation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil: AAPG Bulletin, **85**, 1903–1924.

Pereira, R., D. Mondini, and D. Donno, 2018, Efficient 3D internal multiple attenuation in the Santos basin: 80th Conference and Exhibition, EAGE, Extended Abstracts, https://doi.org/10.3997/2214-4609.201801073.

Van der Neut, J., and K. Wapenaar, 2016, Adaptive overburden elimination with the multidimensional Marchenko equation: Geophysics, **81**, no. 5, T265–T284, https://doi.org/10.1190/geo2016-0024.1.

Wu, X., and B. Hung, 2015, High-fidelity adaptive curvelet domain primary-multiple separation: First Break, **33**, 53–59, https://doi.org/10.1071/ASEG2013ab094.

Ying, L., L. Demanet, and E. Candes, 2005, 3D discrete curvelet transform: Wavelets XI, International Society for Optics and Photonics, 591413.

10.1190/segam2018-2990024.1