Improved imaging of pre-salt targets in the Santos basin off-shore Brazil through attenuation of inter-bed multiples

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This paper was prepared for presentation during the 14th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 3-6, 2015.

Summary

The Santos basin off-shore Brazil contains carbonates in the pre-salt geology that are good candidates for hydrocarbon reservoirs. Imaging these targets is challenged by the presence of highly reflective stratified salt that causes relatively high amplitude inter-bed multiples to interfere with the pre-salt target reflectors. The amplitudes of these multiples are further amplified by the focusing of waves induced by the largely concave shape of the stratified salt. Using a dataset from the Santos basin as an example, we show that inter-bed multiple attenuation can be used to successfully remove the interference due to such multiples, thus providing improved images of the pre-salt targets that facilitate improved interpretation. In this case the attenuation was performed in the migrated domain. We found that using the water-bottom as the only generator of inter-bed multiple reflections turned out to be sufficient to attenuate most of the multiple energy.

Introduction

The Santos Basin off-shore Brazil is an area with complex geology that is currently being explored extensively for the presence of hydrocarbons. The carbonates in the pre-salt, i.e. below the salt, are particularly good candidates for potential hydrocarbon reservoirs. Therefore, accurate and high-resolution imaging of these targets is important.

The salt in the Santos basin is often stratified or contains high-contrast inclusions. Due to the high-contrast of these inclusions, they are excellent reflectors for seismic energy. Moreover, the high contrast ensures that seismic waves that reflect multiple times off of these contrasts, have similar amplitudes as waves that reflect off of these contrasts only once. Such waves are typically referred to as inter-bed multiples.

Since current imaging techniques assume seismic waves to have reflected only once, the presence of inter-bed multiples will cause artefacts in the image, i.e. phantom reflectors at locations in the earth where there are none. Therefore, it is necessary to attenuate these inter-bed multiples prior to imaging. Figure 1a shows an in-line depth-migrated stacked section where no attempt was made to attenuate the inter-bed multiples prior to imaging. It is clear that the inter-bed multiples interfere with the pre-salt targets, thus hampering subsequent interpretation.

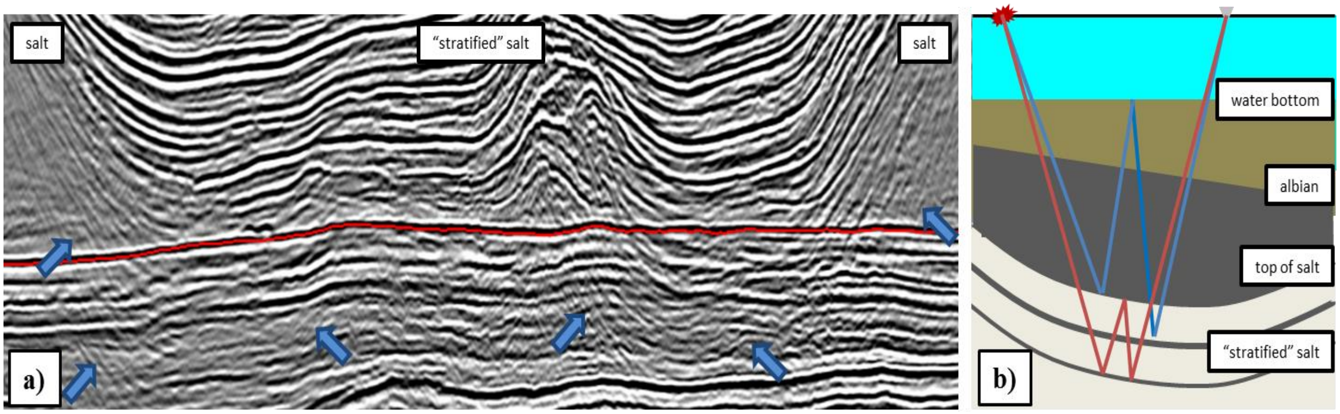

Figure 1. a) Inline depth-migrated stacked image from the Santos Basin area, zoomed on the pre-salt formations. The base of salt is indicated by the red line. Inter-bed multiples, indicated by the blue arrows, interfere with the image of the pre-salt target. b) Diagram of two different ray-paths depicting inter-bed multiples. The blue line indicates an inter-bed multiple generated by the water-bottom, while the red line indicates an inter-bed multiple generated by the top of salt.

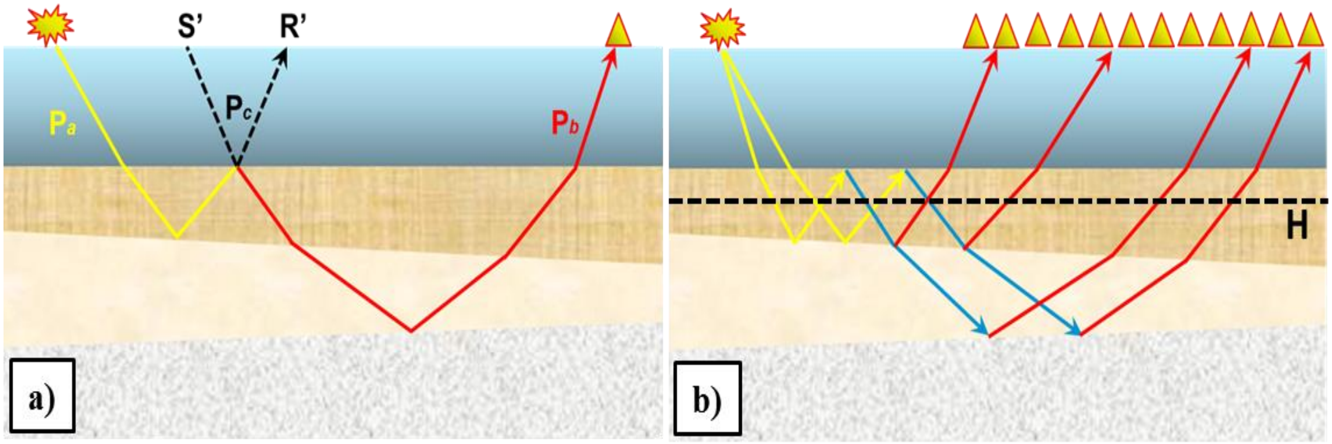

Figure 2. a) Jacubowicz's method: P_a is convolved with P_b, and correlated with P_c to model the inter-bed multiple; b) wavefield extrapolation method: a horizon H separates areas where only upward or downward reflections occur and waves are propagated carrying out inter-bed multiple reflections generated by any reflector above H.

We note that the interference of the inter-bed multiples with the pre-salt reflectors is particularly strong below the concave-shaped stratified salt layers that act as a lens focusing the energy, thus enhancing the amplitudes of the inter-bed multiples (Pica and Delmas, 2008). Figure 1b shows two schematic ray-paths depicting inter-bed multiples generated by the stratified salt, one generated by the water-bottom (blue line) and one generated by the top of salt (red line).

Originally the attenuation of multiples was limited to multiples that were generated by the free surface. Such multiple removal is referred to as Surface-Related Multiple Elimination (SRME) (Verschuur, 1991). In this method the multiples are predicted by convolving the data with itself. For example, convolving a primary with a primary, a first order multiple is predicted, while convolving a primary with a multiple, a higher-order multiple is predicted. Because the multiples are estimated using a convolution of the data with itself, the method is purely data-driven. Jakubowicz (1998) extended this method to allow the prediction of inter-bed multiples by adding a cross-correlation step. This cross-correlation step essentially models an inter-bed multiple by removing, after convolution of the data with itself, that part of the energy that can be viewed as a primary reflection (see Figure 2a). Therefore, this method is in principle also fully data-driven; however, the method can be made computationally substantially more efficient by providing an estimate of the reflector that generates the inter-bed multiple. It then becomes important to accurately identify the main multiple-generating reflector. We note that in this work, the multiple-generating reflector only reflects energy downward.

In addition to data-driven methods (e.g. Ikelle, 2004; Luo *et al*., 2007) there are other methods which rely on the availability of a velocity model, and as such are at least partially model-driven. Pica and Delmas (2008) provide a wavefield-extrapolation-based method that uses both a macro-velocity model as well as a migrated seismic section to model inter-bed multiples (see also Griffiths *et al.*, 2011). The method assumes an estimate of an interface that separates the model into two areas, one in which only downward, and one in which only upward reflection occurs (Figure 2b). By doing so, the inter-bed multiples can subsequently be modelled using the measured data. The one-way wave-equation is used to extrapolate the measured data to the reflectors in the seismic image. Therefore, it is a hybrid method that depends on both the data and the velocity model.

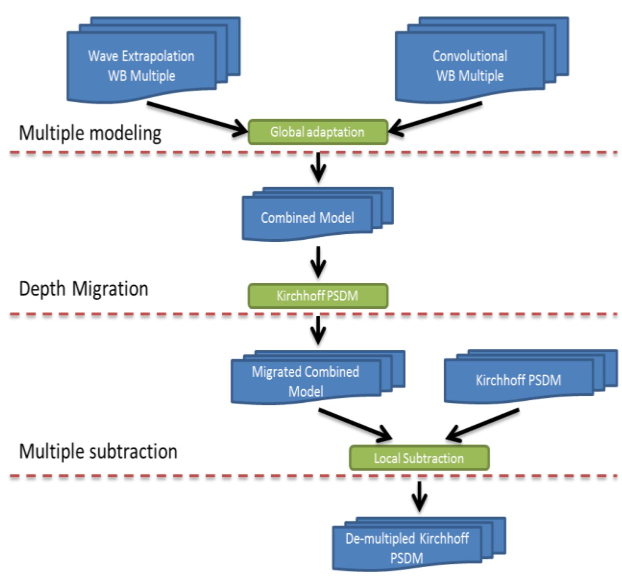

Figure 3. Workflow for the implementation of inter-bed multiple attenuation.

We present the combined use of both these inter-bed multiple attenuation (IMA) methods to attenuate such multiples in the data from a large (approximately 3500 km^2) marine survey in the Santos Basin in the deep offshore waters of Brazil. This work was established through a strategic Technological Collaboration Agreement between PETROBRAS and CGG.

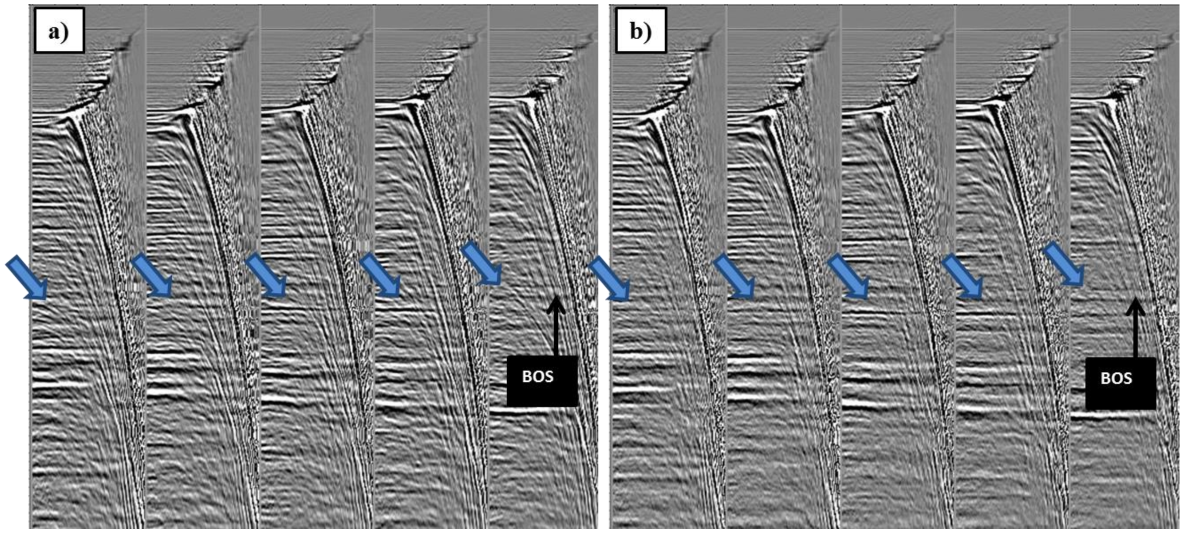

Figure 4. Common image gathers prior to (a) and after (b) application of IMA (a). The arrows point at areas of improvement close to the base of salt (BOS, indicated by the black arrow). The inter-bed multiples interfering with the primary events are attenuated. IMA is most effective on the near to mid offsets, leaving some room for further improvement at the farthest offsets.

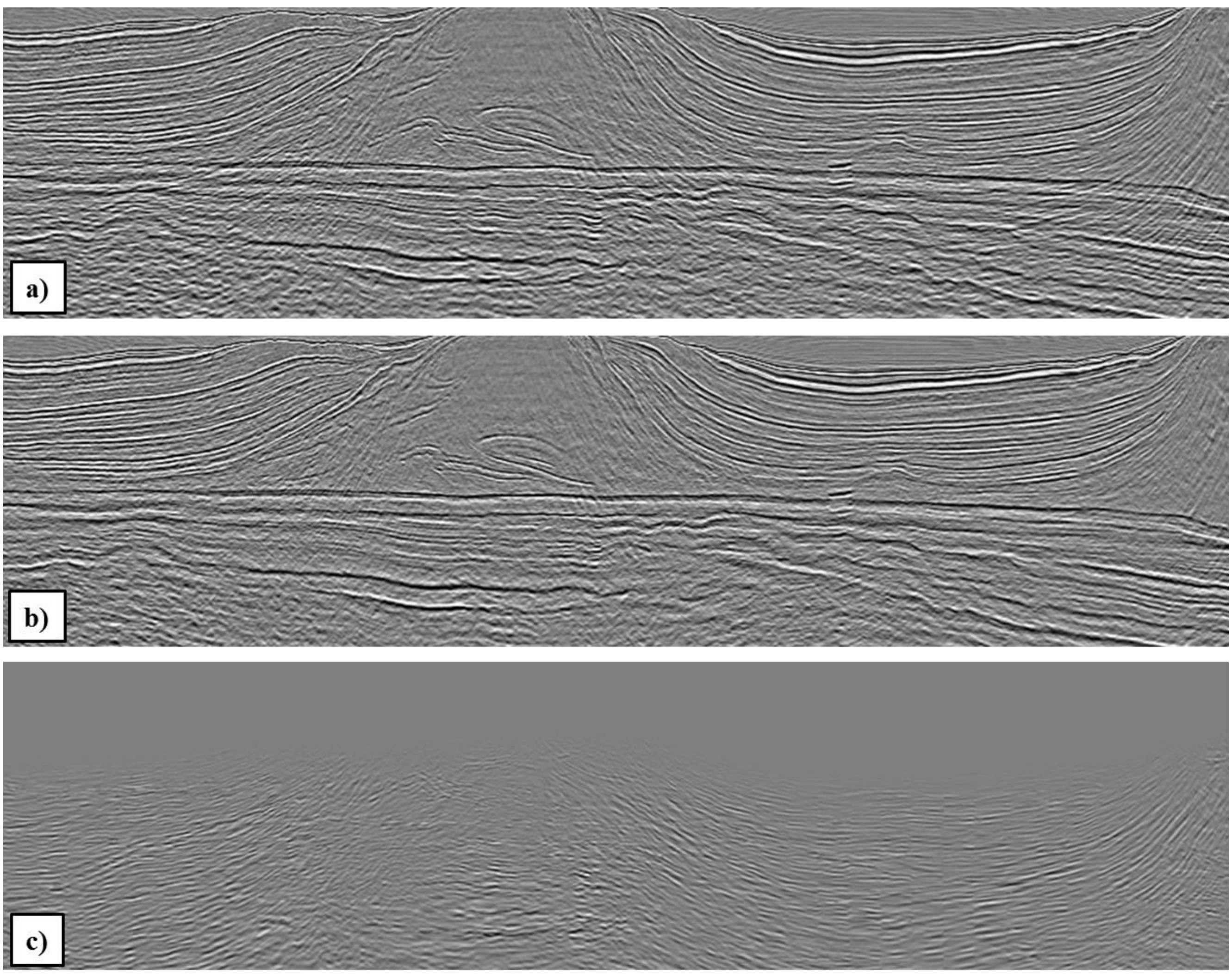

Figure 5. Common offset gather (offset is 273 m) before (a) and after (b) application of IMA, and the difference (c). The inter-bed multiples interfering with the pre-salt area are attenuated well, even in areas where the dip of the inter-bed multiples are similar to that of the primary events.

Internal Multiple Attenuation

Usually multiple attenuation is done prior to imaging. The effectiveness of the attenuation is then judged on the common mid-point and common offset gathers, and once a satisfactory result is obtained, the resulting data is migrated. Multiple attenuation, however, almost always involves an adaptive subtraction procedure because the multiple prediction is usually not accurate enough to allow straightforward subtraction. Adaptive subtraction can benefit from the (partial) collapse of diffractions in the migrated domain, thus helping with the final multiple attenuation result. Doing the attenuation in the migrated domain, however, requires additional migration of the estimated inter-bed multiples prior to subtraction. Therefore, IMA is typically not performed in the migrated domain due to the added computational expense of the necessary additional migration. In this case, however, a migrated volume before IMA was already available from a previous processing effort. Therefore, we chose to do the subtraction in the migrated domain. The general workflow thus consisted of three subsequent steps: modeling of the inter-bed multiples, migration of these multiples, and adaptive subtraction (see Figure 3). The migration was done using a Kirchhoff PSDM.

We tested both Jacubowicz' (1998) and Pica and Delmas' (2008) methods. In both cases an estimate of the reflector generating the inter-bed multiples is needed. The most plausible candidates to generate the inter-bed multiples were identified to be the water-bottom, the top of the Albian formation, and the top of salt. After extensive testing using both synthetic and field data, we found that the water-bottom could explain most of the inter-bed multiple energy interfering with the pre-salt reflectors. Therefore, the water-bottom was chosen as the main inter-bed (downward) multiple generator. All results shown in this work were obtained using the water-bottom as the only inter-bed multiple generating reflector.

The data-driven method by Jacubowicz was found to provide a better prediction for the mid to far offsets, while the partially model-driven method from Pica and Delmas provided a better prediction for the near offsets. This is to be expected, because Jacubowicz' method suffers from the lack of azimuths in the data needed to accurately predict the near offsets. For these near offsets the partially model-driven method can produce some of the needed azimuths through wave-field extrapolation. At the same time, for the longer offsets, the partially model-driven method suffers from possible inaccuracies in the velocity model, while the data-driven method is immune to such errors as it works only with the recorded data itself To obtain the best possible overall prediction, the predictions from both methods were therefore combined into one model of estimated inter-bed multiples (Figure 3). During the final adaptive subtraction stage, special care was taken to avoid affecting the amplitudes of the primaries. The subtraction was done in 3D in the common-offset x-y-z domain, thus giving equal importance to both the in-line and cross-line directions.

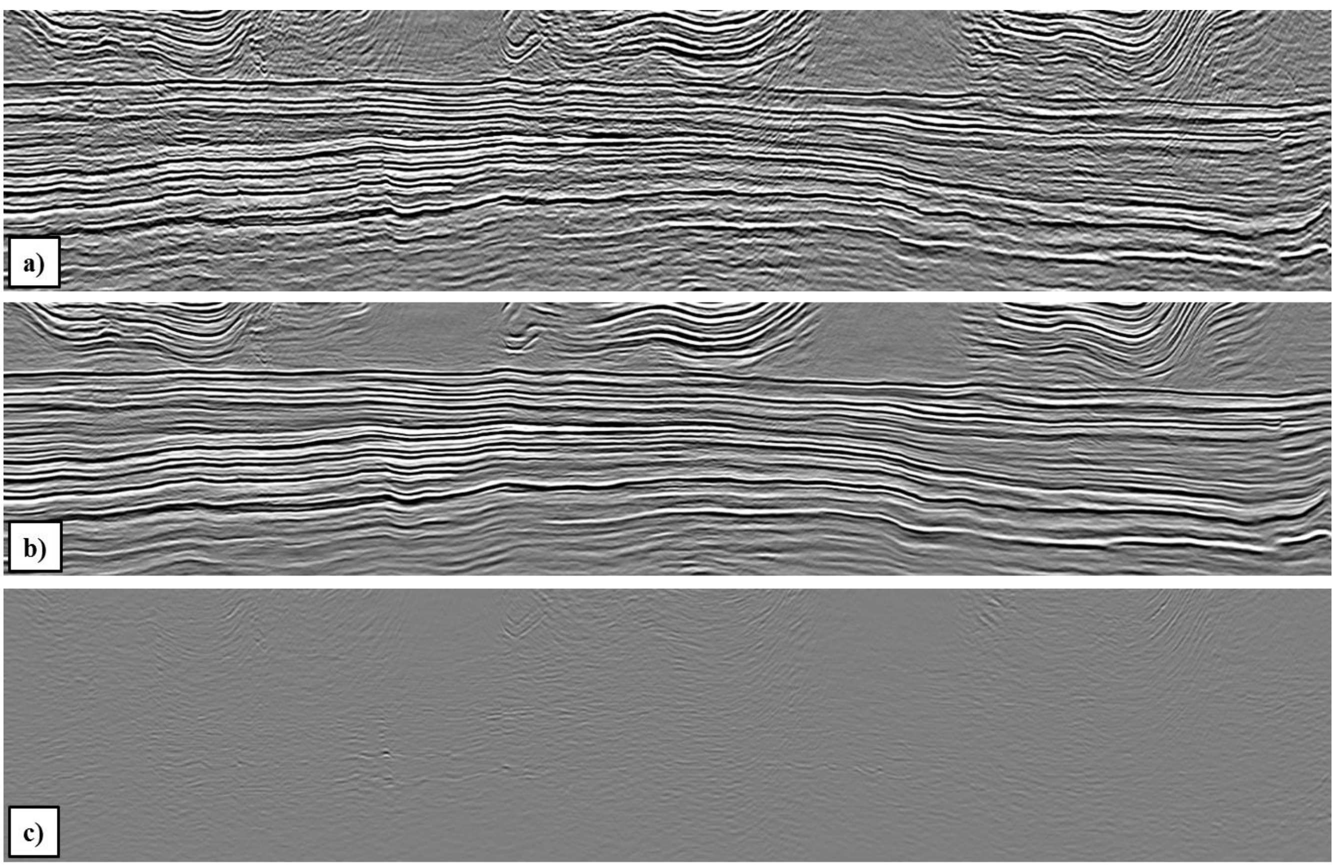

Figure 6. Stacked migrated inline section before (a) and after (b) application of IMA and their difference (c). IMA has successfully removed the inter-bed multiples from the stratified salt generated by the water-bottom that interfere substantially with the pre-salt targets. The difference indicates that only inter-bed multiples were removed since it shows no resemblance to the pre-salt image of the primaries (see

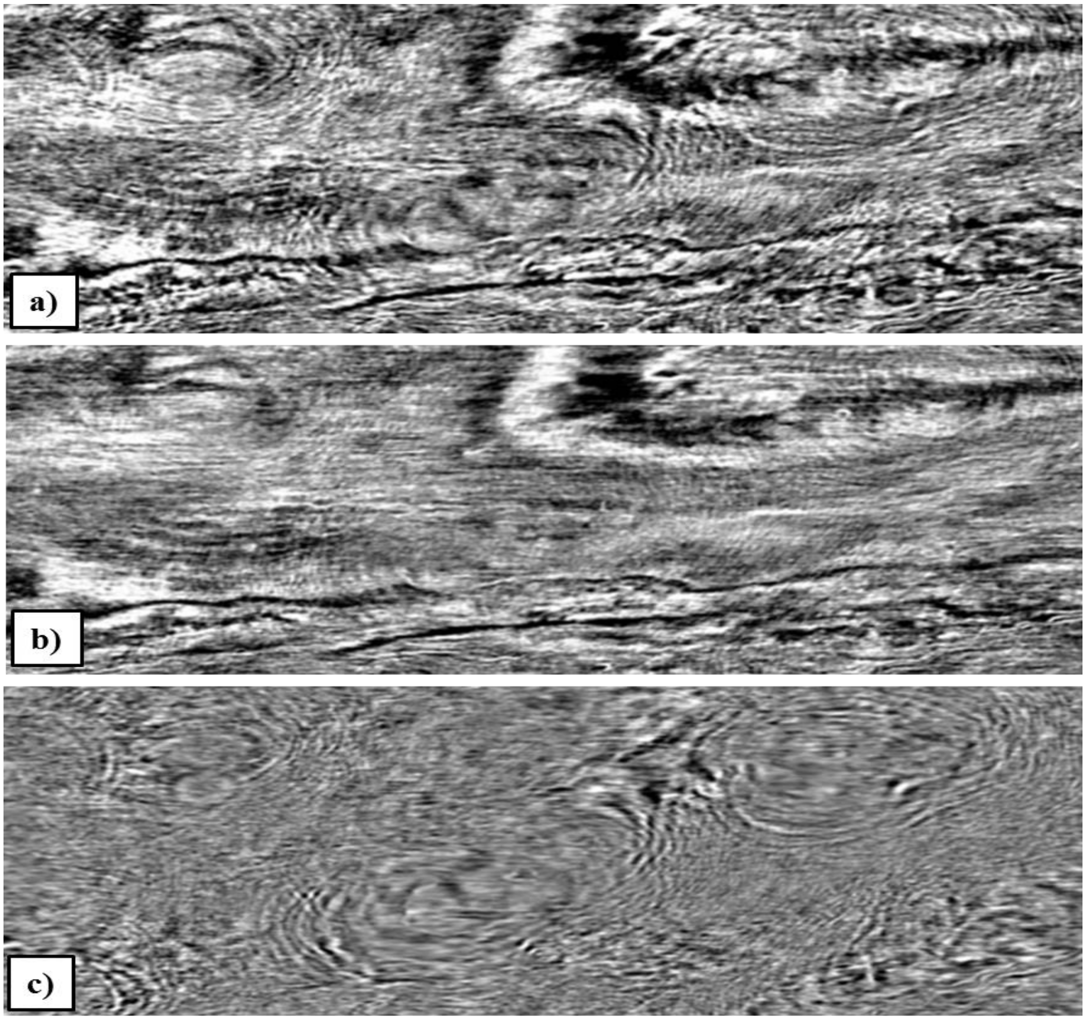

Figure 7. Structural slice along the base of salt through the migrated volume before (a) and after (b) application of IMA, as well as the difference (c). It is evident that the interference of the inter-bed multiples with the base of salt has been substantially reduced, while preserving the imaged primaries.

Field data example

Figure 4 shows the impact of the application of IMA on several pre-stack image gathers. These image gathers indicate that IMA is particularly effective on the near to mid offsets where the difference in move-out between the primaries and the multiples is relatively small. Multiple-attenuation methods that depend on a difference in move-out, such as Radon filtering, typically fail at such offsets. On the far offsets, some multiple energy still remains, leaving some room for further improvement.

Figure 5 shows a common-offset gather for one migrated inline before (Figure 5a) and after (Figure 5b) IMA as well as their difference (Figure 5c). The interference caused by the inter-bed multiples with the pre-salt targets below the concave shaped stratified salt layers is clearly visible. The difference (Figure 5c) shows that indeed the inter-bed multiple energy that was removed has mostly the same structure as the image of the overlying salt, while showing no resemblance to the geological structure below the base of salt This indicates that the primaries were not affected by the adaptive subtraction and that indeed only inter-bed multiple energy was removed. We note that even in locations where the dip of the predicted inter-bed multiples is close to the structural dip of the imaged primaries, IMA has successfully attenuated the inter-bed multiple while preserving the primaries. Such locations are typically challenging for adaptive subtraction. We emphasize that by using the water-bottom as the only inter-bed multiple generating reflector, we were able to model and subsequently subtract most of the inter-bed multiple energy.

Figure 6 shows an inline stacked migrated section before (Figure 6a) and after (Figure 6b) IMA as well as their difference (Figure 6c). The final stacked image shows that the interference due to the inter-bed multiples has been successfully removed, providing a substantially improved image of the pre-salt targets. Again, as is evident from the difference section, even in locations where the inter-bed multiples show a comparable dip to the primaries, IMA attenuated the multiples well while preserving the primaries.

The interference of inter-bed multiples with any key horizons can hamper reservoir characterization studies and complicate future interpretation. Figure 7 shows a structural slice along the base of salt horizon before (Figure 7a) and after (Figure 7b) application of IMA, and the difference (Figure 7c). Prior to application of IMA the interference of the inter-bed multiples is clearly visible as roughly circularly shaped artefacts. IMA successfully attenuates these artefacts thus facilitating further improved interpretation.

Conclusions

We show the impact of the successful application of IMA on both pre-stack and post-stack images from pre-salt targets in the Santos Basin off-shore Brazil. Imaging and interpretation of these targets is usually challenged by the interference of inter-bed multiples. We show that IMA successfully attenuates this interference, while leaving the image of the primaries unaffected. The extra care given to preserving the amplitudes of the imaged primaries during the adaptive subtraction allowed the successful removal of inter-bed multiples even in areas where the structural dip of the imaged primaries is similar to that of the multiples. The images with the inter-bed multiples removed facilitate future improved reservoir characterization and interpretation. In this case, we found that modeling the inter-bed multiples using the water-bottom as the only (downward) inter-bed multiple-generating reflector was sufficient to attenuate most of the multiple energy interfering with the pre-salt target horizons. The adaptive subtraction was applied in the migrated domain.

Acknowledgements

We would like to thank Petrobras and CGG for permission to publish this work and Malcolm Griffiths, Sylvain Leroy, Ekaterina Kneller, Luis D'Afonseca and Antonio Pica from CGG for their support. This work was established as part of a strategic Technological Collaboration Agreement between PETROBRAS and CGG.

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