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The Impact of Inter-bed Multiple Attenuation on the Imaging of Pre-salt Targets in the Santos Basin Off-shore Brazil

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SUMMARY

The carbonates in the pre-salt area of the Santos basin off-shore Brazil are good candidates for reservoirs of hydrocarbons. The presence of highly reflective stratified salt in this basin, combined with the focusing of energy due to the concave shape of these reflectors, causes relatively high amplitude inter-bed multiples to interfere with pre-salt reflectors. This multiple energy hampers the imaging and interpretation of these targets. We show that inter-bed multiple attenuation can be used to successfully remove the interference due to such multiples, thus improving the imaging of the pre-salt targets and facilitating improved interpretation. In this case, using the water-bottom as the only inter-bed multiple-generating reflector turned out to be sufficient to attenuate most of the multiple energy. The attenuation of the multiples was performed in the migrated domain.

Introduction

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

The salt in this area is often stratified or contains high-contrast inclusions that are excellent reflectors for seismic energy. Due to the relative strength of such reflections, they can be the source of multiply reflected energy between geological layers, also known as inter-bed multiples. Since most current seismic imaging techniques are limited to singly-reflected (or primary) seismic events, these inter-bed multiples can, if not effectively attenuated prior to imaging, interfere with the image. This is particularly important for the pre-salt targets. Figure 1a shows an in-line 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 any subsequent interpretation. Figure 1b shows two schematic ray-paths depicting inter-bed multiples generated by the stratified salt. 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).

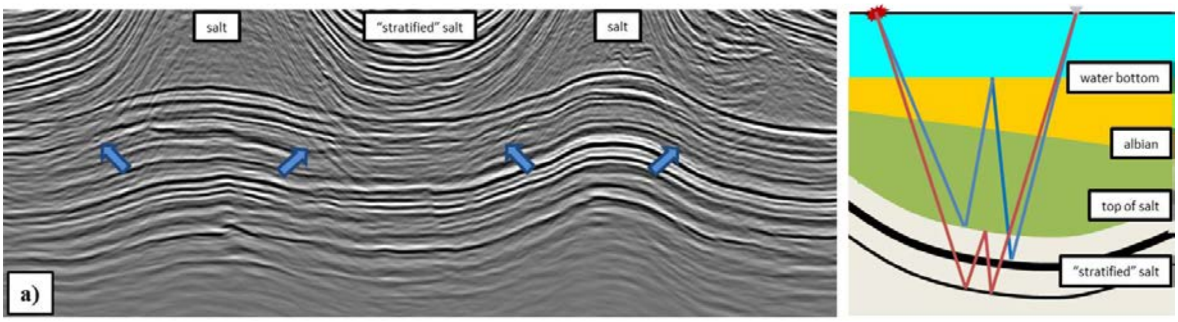

Figure 1 a) *Inline stacked section from the Santos Basin area, zoomed on the pre-salt formations. Inter-bed multiples indicated by the blue arrows interfere with the image of the pre-salt target.* ***b)*** *Diagram of two different ray-paths depicting inter-bed multiples.*

The attenuation of multiples was originally restricted to multiples generated by the air-water interface in marine seismic data. Such multiple removal is referred to as Surface-Related Multiple Elimination (SRME). This method is purely data-driven because it estimates the multiples by convolving the data with itself. 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 (Figure 2a). In principle this method is also fully data-driven, however, the method can be made substantially more computationally efficient if an estimate of the inter-bed multiple generating reflector is available. It is therefore important to identify the main multiple-generating reflector. In this work, the multiple-generating reflector only reflects energy downward.

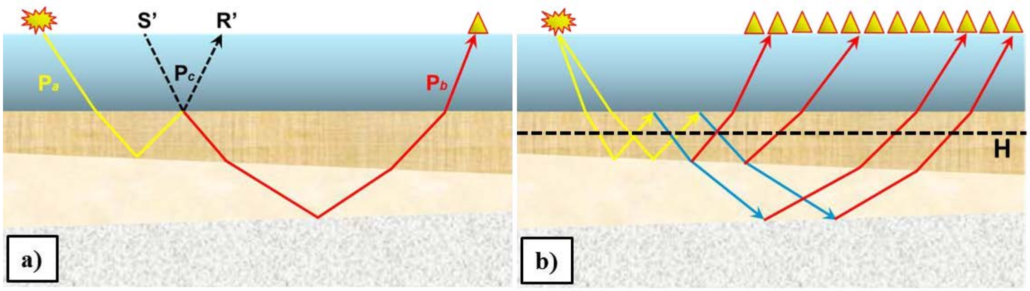

Figure 2 a) *Jacubowicz's method: Pa is convolved with Pb, and correlated with Pc to model the inter-bed multiple;* ***b)*** *wavefield extrapolation method: a horizon H separates areas where only upward or downward reflections occur and waves are propagated carrying out inter-bed multiple reflections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

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). By estimating an interface that separates the model into two areas, one in which only downward and one in which only upward reflection occurs, the inter-bed multiples can be modeled from the measured data (Figure 2b). The one-way wave-equation is used for wave-field extrapolation of the data to the reflectors in the seismic image. As such it is a hybrid method that depends on both the data as well as on the velocity model.

Here we show the application of these inter-bed multiple attenuation (IMA) methods applied to a large (approximately 3500 km^2) marine survey acquired over the Santos Basin in the deep offshore waters of Brazil. This work was established through a strategic Technological Collaboration Agreement between PETROBRAS and CGG.

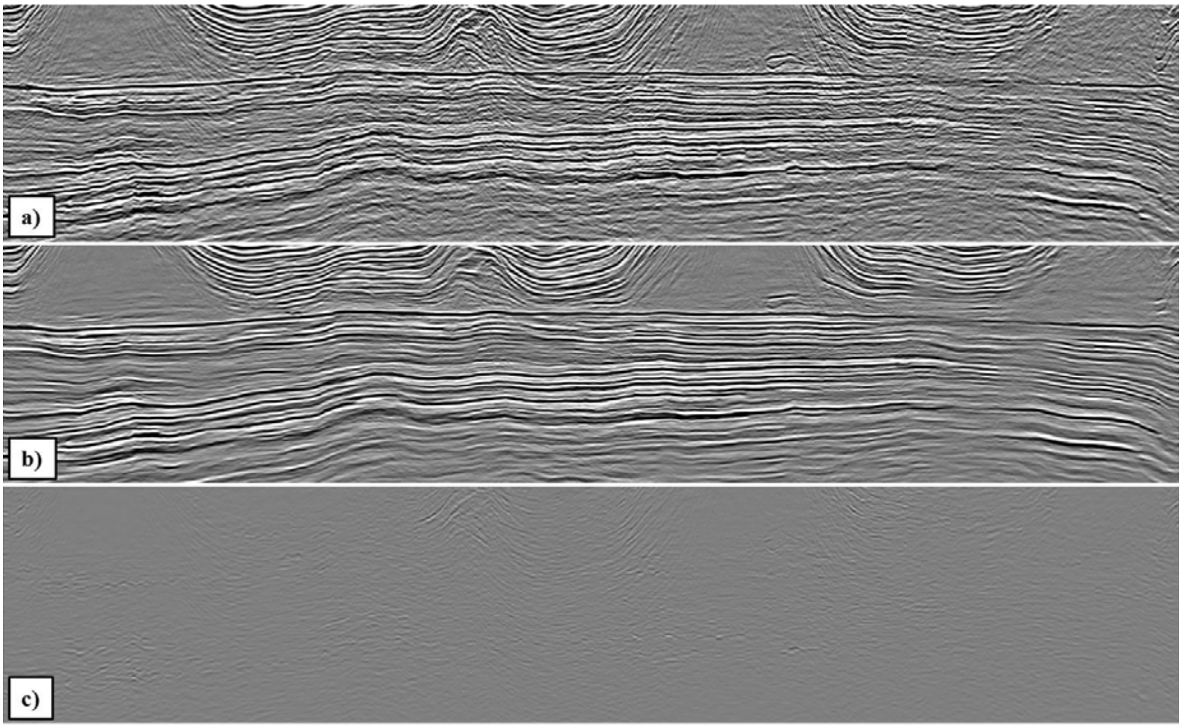

Figure 3 a) *Inline stacked migrated section before IMA,* ***b)*** *after IMA, and* ***c)*** *the difference. IMA with the water-bottom as the inter-bed multiple generator provides a substantial reduction in the interference of the inter-bed multiples and the pre-salt reflectors.*

Method

Multiple attenuation is usually performed in the pre-migrated domain. In the migrated domain, however, the necessary adaptive subtraction can benefit from the (partial) collapse of diffractions upon migration. Performing the multiple attenuation in the migrated domain requires the additional step of migrating the estimated inter-bed multiples. In this case, a migrated volume before IMA was available from a previous processing effort, and therefore no additional computational overhead was needed. 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. 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. Extensive testing on both synthetic and field data indicated that the water-bottom could explain most of the inter-bed multiple energy interfering with the pre-salt reflectors. Therefore all results shown in this work are obtained using the water-bottom as the main inter-bed multiple generator.

While testing both methods of inter-bed multiple prediction, we found that the data-driven method by Jacubowicz provided a better prediction on the mid to far offsets, whereas the partially model-driven method from Pica and Delmas provided a better prediction for the near offsets. To obtain the best possible quality prediction, the predictions from both methods were combined. 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 the in-line and cross-line directions.

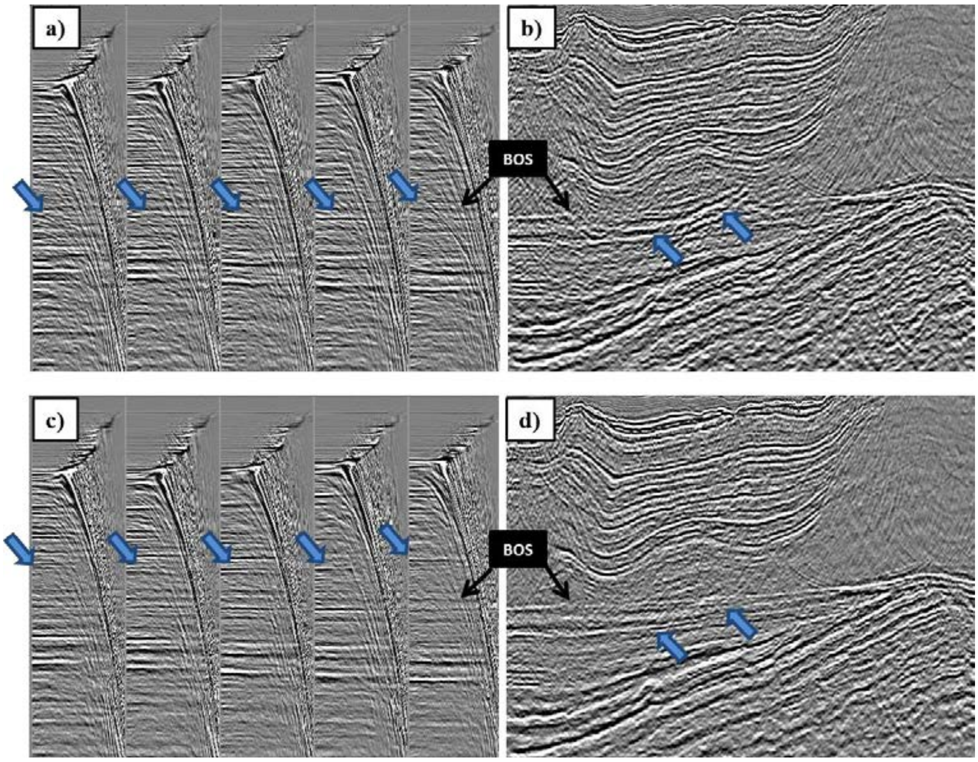

Figure 4 *Impact of the application of IMA on the pre-stack common-image (a and c) and common-offset (b and d) gathers (offset is 723m). Top: before IMA; bottom: after IMA. The arrows indicate the places of improvement. The common-offset gathers show the successful removal of an inter-bed multiple overlapping with a primary with almost the same dip, improving the image of the base of salt.*

Application to field data

Figure 3 shows an in-line migrated and stacked section before and after application of IMA. The interference caused by the inter-bed multiples with the pre-salt target below the concave shaped stratified salt layers, is clearly visible (Figure 3a). Application of IMA effectively removes most inter-bed multiple energy (Figure 3b). We emphasize that by using only the water-bottom as the inter-bed multiple generator, we were able to model and subsequently subtract most of the inter-bed multiple energy.

Figure 4 shows the impact of the application of IMA on some pre-stack image gathers as well as a common-offset gather. The image gathers show that IMA was 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 these offsets. On the far offsets, some multiple energy still remains, leaving room for further improvement. We also note the presence of an inter-bed multiple (Figure 4b, indicated by the arrows) interfering with the base of salt (BOS) on the common-offset section. Application of IMA attenuates this multiple effectively, although it has almost the same dip as the BOS and, therefore, its attenuation is generally challenging.

The availability of the spatial variation of amplitudes along horizons can be of particular benefit to reservoir characterization studies. The interference of inter-bed multiples with any key horizons can hamper such studies and thus interpretation as well. Figure 5 shows the RMS amplitude extracted along the BOS horizon both before (Figure 5a) and after (Figure 5b) application of IMA. Before the application of IMA the interference of the inter-bed multiples is clearly visible as circularly shaped artefacts. IMA successfully attenuates these artefacts thus facilitating more accurate interpretation.

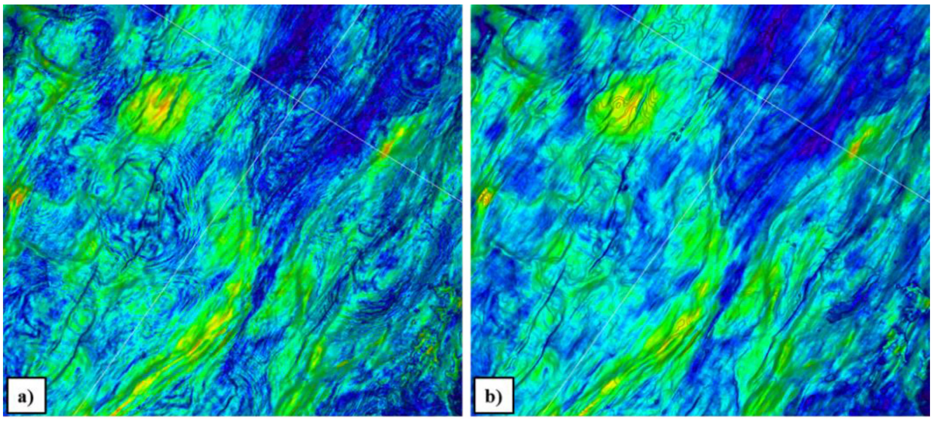

Figure 5 *RMS maps extracted along BOS:* ***a)*** *RMS map before IMA application with clearly visible circularly shaped inter-bed multiple interference;* ***b)*** *after IMA application this interference has been successfully attenuated.*

Conclusions

Imaging and interpretation of pre-salt targets in the Santos basin off-shore Brazil can be hampered by the interference of inter-bed multiples with key target horizons. We show the impact of the successful application of IMA on both pre-stack and post-stack images as well as on an RMS amplitude map extracted along the BOS. After IMA the interference is successfully attenuated thus facilitating improved reservoir characterization and interpretation. Modeling the inter-bed multiples using the water-bottom as the only inter-bed multiple-generating reflector proved sufficient to attenuate most of the multiple energy interfering with the pre-salt target horizons. The adaptive subtraction was applied in the migrated domain.

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