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Pre-salt Depth Imaging of the Deepwater Santos Basin, Brazil

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SUMMARY

Several discoveries, such as Tupi, Bem-Te-Vi, Parati, and Guara, have been announced in the Santos Basin off the coast of Brazil. Most of these recent discoveries have been in pre-salt layers. These layers were well imaged by a salt flood volume produced in 2003, but distortions in the base of salt (BOS) and pre-salt layers were still obvious. Therefore, a depth migration with a complete salt model is necessary for correctly positioning the reservoir structures. In order to obtain high-quality subsurface images, building an accurate velocity model and using the optimal migration algorithm for the geology is paramount. For pre-salt imaging, not only the pre-salt velocity, but also the overburden velocities, i.e. sediment velocities, salt velocities and salt geometry, are critical. The unique aspects of the local geology in the Santos Basin make building the velocity model challenging. The three major issues are: 1) the presence of a thin Albian layer above the salt, 2) the sensitivity of the top of salt (TOS) picking to pre-salt imaging, and 3) the existence of evaporite layers within the salt. The following techniques are introduced to improve the accuracy of the velocity model and the pre-salt image: Albian layer tomography, iterative TOS interpretation, and intra-salt tomography.
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Introduction

Several discoveries, such as Tupi, Bem-Te-Vi, Parati, and Guara, have been announced in the Santos Basin off the coast of Brazil. Most of these recent discoveries have been in pre-salt layers. These layers were well imaged by a salt flood volume produced in 2003, but distortions in the base of salt (BOS) and pre-salt layers were still obvious. Therefore, a depth migration with a complete salt model is necessary for correctly positioning the reservoir structures. In order to obtain high-quality subsurface images, building an accurate velocity model and using the optimal migration algorithm for the geology is paramount. For pre-salt imaging, not only the pre-salt velocity, but also the overburden velocities, i.e. sediment velocities, salt velocities and salt geometry, are critical. The unique aspects of the local geology in the Santos Basin make building the velocity model challenging. The three major issues are: 1) the presence of a thin Albian layer above the salt, 2) the sensitivity of the top of salt (TOS) picking to pre-salt imaging, and 3) the existence of evaporite layers within the salt. The following techniques are introduced to improve the accuracy of the velocity model and the pre-salt image: Albian layer tomography, iterative TOS interpretation, and intra-salt tomography.

Reverse time migration (RTM) is considered the most accurate migration algorithm (Zhang and Sun 2009). It is able to better image pre-salt events under the rugose TOS compared to Kirchhoff migration, which has a single ray-path limitation for imaging complex geology. However, RTM is computationally intensive and the computing load increases with frequency. Despite this extra cost, high-frequency RTM is essential to image pre-salt structures and stratigraphy in the deepwater Santos Basin. Our study in the Tupi area showed that an abrupt amplitude change appeared when applying low-frequency RTM. The amplitude break dissipated as higher frequencies were migrated.

Further improvement of the pre-salt images may be possible by introducing anisotropy in the model building and migration. Ignoring the anisotropic effects may incorrectly position salt flanks and distort the BOS and pre-salt structures. Furthermore, the dip angles of some deep basins can reach more than 50 degrees. With such high-dip bedding, tilted transverse isotropy (TTI) may provide significant improvement to the accurate positioning of these events.

In the following sections, the pre-stack depth migration (PSDM) velocity model building flow for deepwater Santos Basin data is presented, highlighting the three key steps in the model building flow: Albian layer tomography, iterative TOS interpretation and intra-salt tomography. Then, Kirchhoff migration and RTM comparisons that illustrate the uplift of RTM are shown. Finally, a TTI PSDM test is used to demonstrate the benefit of TTI.

Velocity Model Building Flow in the Santos Basin

A top-down process was used to build the velocity model for the Santos Basin. It included: 1) Water bottom determination, 2) Sediment tomography, 3) Albian layer tomography, 4) Iterative TOS interpretation, 5) Salt flood migration, 6) Salt layer tomography, 7) BOS interpretation, and 8) Subsalt velocity update. The first step was to determine the water bottom surface. It was interpreted on a water flood migration volume, resulting in less than 3 m mis-ties when compared with well measurements. Tomographic inversion (Zhou, 2003) was then used to derive the velocity of the sediment region. A relatively smooth sedimentary velocity field was obtained after several iterations of the tomographic updates.
In the Santos Basin, there is an Albian layer directly above the Aptian salt (Rosenfeld and Hood, 2006). Inside the study area, the Albian layer appears to have its own unique character compared to the sediment layer above it. In general, the Albian layer is thin and its velocity gradient is higher than the normal sediment compaction trend. Also, except for the top of the Albian layer that is a bright seismic reflector, other events in the Albian layer have relatively weak amplitudes compared to the sediment beddings. If optimal event picking and tomography parameters are chosen for the sediment layers, the velocities for most of the Albian layer would not be updated correctly. To resolve this problem, a layer-constrained tomographic velocity update between the top of Albian (TOA) and TOS was performed. The parameters for event picking and tomographic inversion were optimized specifically to handle the Albian layer. With the Albian tomography, the gathers became flatter in both the Albian and salt layers after applying a salt flood migration. This indicates that a more accurate velocity model was obtained after the Albian layer tomography.

The next step was to interpret the TOS surface. Unlike the top of salt in the Gulf of Mexico, most of the TOS events in this area are buried in a sequence of reflectors, making it difficult to pick the correct one. Our study demonstrates that the images of the BOS and pre-salt events are very sensitive to the position of the TOS. In Figure 1a, the BOS and pre-salt events are sagging. Picking TOS slightly deeper (Figure 1b) reduces the sag and makes the BOS straighter and better focused. Due to the sensitivity of the pre-salt image to the TOS interpretation, the TOS horizon could not be finalized in a single step. Iterative TOS interpretation was necessary to resolve this ambiguity. The BOS and pre-salt images were used to evaluate the necessity of modifying the TOS interpretation. With every modification to the TOS, another salt flood migration was needed to confirm the change.

After finalizing the TOS interpretation, a salt flood migration with a constant salt velocity of 4530 m/s was performed. In the traditional PSDM velocity model building flow, this volume would be used for BOS interpretation and the velocity in the salt layer would remain constant in the final velocity model. Recently, Ji et al. (2010) proposed dirty salt velocity inversion to accommodate velocity variation inside salt caused by scattered sediment inclusions and it shows promising improvement in BOS and subsalt imaging in the Gulf of Mexico (GOM). However, in the Santos Basin, the layered evaporites within the salt body show continuous events with strong reflections, as opposed to the “dirty salt” character of the GOM. This provides an opportunity for updating the salt layer velocity with tomography. An intra-salt tomography step was introduced after the constant salt velocity flood to improve the velocity model in the vicinity of the layered evaporites. By carefully picking the residual
curvatures of those events, a better velocity field inside the salt (evaporites) layer was obtained through tomographic inversion.

Compared to the TOS, the BOS was relatively simple to interpret in the study area. The main criterion for evaluating the correctness of the velocity field above the BOS was the assumption that the shape of the BOS should not be geologically complex. Below the BOS, we observed a faster velocity trend, which was updated through tomographic inversion (Zhou, 2003). This PSDM velocity model building flow produced a better velocity field and allowed better pre-salt images to be obtained.

Utilizing Reverse Time Migration (RTM)

The RTM method has existed since the 1980’s (Baysal et al., Baysal 1983, and Whitmore 1983). It migrates data directly using the two-way wave equation. The advantages of RTM include preserving true amplitude and the more accurate handling of complex structures without dip angle limitations (Zhang and Sun, 2009). However, RTM is very computationally intensive, and the computing load increases with frequency. The study in the Tupi area showed that some of the BOS and pre-salt events contain high frequency information which cannot be correctly imaged with low-frequency RTM. High frequencies are essential for correctly imaging pre-salt structures and stratigraphy, so any attempt at low-frequency RTM in order to save computer time defeats the very purpose of using RTM. Figure 2a shows the Kirchhoff migration result. Amplitudes on the BOS and pre-salt events are relatively consistent, but do display some amplitude shadows. Figure 2b shows a 30 Hz RTM result. The BOS and pre-salt events on the left hand side are much weaker than the one on the right hand side with an obvious amplitude break in the middle near the Tupi well location. With the 40 Hz RTM shown in Figure 2c, the amplitude at the BOS is comparable to the Kirchhoff result with a slight improvement. Increasing the frequency cutoff to 60 Hz (Figure 2d) further improves the amplitude and resolution obtained in the pre-salt image.

Figure 3 shows another comparison of Kirchhoff migration (Figure 3a) and RTM (Figure 3b) in both inline and crossline directions. In this section, the TOS rapidly changes, causing extremely poor imaging of the BOS and pre-salt events in the Kirchhoff result (marked with a circle). In the RTM result, the blank pre-salt zone below the rugose TOS where the Kirchhoff result failed is fairly well imaged. The BOS and pre-salt events are more continuous throughout the RTM section and can be easily interpreted.
Benefits of TTI Imaging

Huang (2008) proposed a TTI velocity model building flow that resulted in improvements on salt flank images in the GOM. A similar TTI PSDM test was conducted in the Santos Basin and produced some promising results in the salt flank positioning and the BOS images. A lack of publicly available well information in the Santos Basin makes it difficult to determine the anisotropy level, but seismic data indicates that anisotropy does exist in this area. In this test, constant values for $\varepsilon$ and $\delta$ ($\varepsilon=5.1\%$ and $\delta=3\%$) were used in the sedimentary area. The symmetry axis was assumed to be perpendicular to the sedimentary bedding, so it was spatially variant. $V_0$ was updated with multiple iterations of 3D TTI tomographic inversion. After the TTI sedimentary velocity updates, the TOS was interpreted. Below the TOS, the velocity volume was flooded with a constant salt velocity. Migrations with the isotropic and TTI models are compared in Figure 4. For comparison purposes, a constant salt flood model was used. The BOS from the isotropic migration (Figure 4a) is pushed down in the region below the center of the basin where the salt body is thin. The TTI migration, shown in Figure 4b, makes the BOS flatter and more continuous. Also the mini-basin becomes narrower and shallower. Our test indicates that a TTI velocity field is required for maximum image quality.
Conclusions

In this paper, we presented a PSDM velocity model building flow in the deepwater Santos Basin, highlighting the three key steps in the model building flow: Albian layer tomography, iterative TOS interpretation and intra-salt tomography. This flow produced a more accurate velocity model, and allowed us to obtain better pre-salt images through the high-end RTM imaging algorithm. High-frequency RTM is essential to image pre-salt structures and stratigraphy. Compared to Kirchhoff migration, a significant pre-salt image improvement under the rugose TOS was obtained using RTM. Also, an initial TTI PSDM test showed that anisotropic imaging may be important in this area.

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