RTM technology for improved salt imaging in the Santos Basin, Brazil

Ananya Roy* and Nicolas Chazalnoel, CGGVeritas

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Abstract

Reverse time migration (RTM) is now recognized as a powerful imaging tool. With its ability to account for rapid spatial velocity variations and to utilize all wavefront information, RTM can produce superior images of the most complex structures. This is why RTM is frequently used to interpret salt structures in regions known to have complex salt geometries like the Gulf of Mexico. With the application of recent advancements such as Vector Offset Output and 3D sub-surface angle gathers, the imaging capability of RTM is enhanced even further. Vector Offset Output RTM can help interpretation by boosting the signal-to-noise ratio in poorly illuminated areas. RTM 3D angle gathers can improve tomographic velocity inversion by providing useful information near complex salt where other migration algorithms fail to do so. These advances significantly improve an interpreter's ability to define the salt structure and improve the accuracy of the velocity model. In this paper, we demonstrate that significant improvements result when advanced RTM tools are used for salt imaging even in the Santos Basin in offshore Brazil where the salt geology is relatively simple compared to the Gulf of Mexico.

Introduction

RTM is a pre-stack two-way wave equation depth migration which is recognized as being able to produce superior sub-salt images compared to other migration algorithms such as Kirchhoff, control beam migration (CBM) or one-way wave equation migration (Zhang et al., 2009; Etgen et al., 2009). Given the high accuracy of RTM, the sub-salt image quality is now limited by the accuracy of the velocity model which, in turn, is very sensitive to the definition of the salt body. For this reason, RTM is often employed, not only for final migration, but also to assist with salt interpretation in regions where the salt geometry is complex and difficult to image (Reasnor, 2007; Buur and Kuhnel, 2008). An RTM image allows a more conclusive determination of the salt structure and thereby improves the reliability of the velocity model and the final image.

In the case of the Santos Basin in offshore Brazil, it has already been shown that RTM can produce superior final depth images compared to ray-based methods (Huang et al., 2010b). Yet, RTM is scarcely used for salt interpretation or any other phases of velocity model building in this area. CBM is widely used instead because the salt geometry in Santos Basin is known to be mostly tabular and less complex than in areas like the Gulf of Mexico. This paper will show that even in the Santos Basin, there are areas where a CBM image does not allow conclusive determination of the salt structure. RTM technology can greatly improve the image in such areas, leading to more reliable salt interpretation that is crucial to the quality of the final pre-salt image.

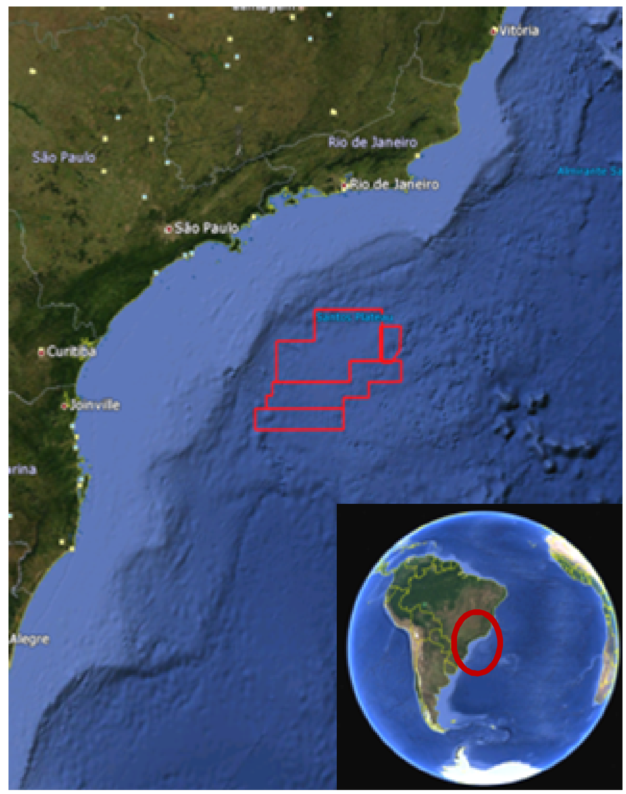

Figure 1: The study area is in a CGGVeritas narrow azimuth survey in the Santos Basin, offshore Brazil. In light of recent discoveries, the pre-salt layers are of special interest in this area.

A recent advancement can separate the RTM image into Vector Offset Output (VOO) components illuminated from different directions (Xu, Q. et al., 2011). We show here that the resulting improvement in the signal-to-noise ratio of poorly illuminated areas can be very useful for salt interpretation.

The salt body in the Santos Basin is a combination of pure halite and sections of layered evaporites. It exhibits large velocity variations that can be estimated by intra-salt tomographic inversion (Huang et al., 2010b). This is typically done using the residual move-out curvature from surface offset CBM gathers. This paper will show that near complex salt, RTM 3D sub-surface angle gathers improve the tomographic velocity update and, in turn, the image of the base of salt and sub-salt events.

Examples in this paper are based on narrow azimuth (NAZ) seismic data acquired from the highlighted region on the map of the CGGVeritas Santos Basin surveys shown in Figure 1. These data were acquired along the East-West direction with 50 m shot spacing, 12.5 m receiver spacing and a maximum offset of 6000 m.

A comparison of CBM- and RTM-derived salt geometries

In the test area, a salt model interpreted purely from CBM images had already been built and showed the presence of steep salt flanks and overhangs between narrow sedimentary basins. Figure 2a shows the CBM image of a line migrated using a second sediment flood model. This model has a constant salt velocity inserted in the upper section of the salt overhang structures. At this stage of model building, the shallow parts of all salt overhangs have been defined and a migration with this model should image the remaining salt structures underneath. However, the CBM image contains a large number of migration swings that can mislead an interpreter. Figure 2b is a 35 Hz RTM image migrated using the same velocity model. This image reveals the salt structure with much greater clarity and was much easier to interpret.

Two independent salt interpretations were derived from the CBM and RTM images and were used to build two different salt flood models. Figure 3 compares these two velocity models overlaid on the RTM images migrated using each model. The model built on the CBM image of Figure 2a shows a shallow salt body isolated from its large, deeper feeder (Figure 3a). The model built on the clearer RTM image of Figure 2b shows that the shallow salt is actually connected to a much smaller deep feeder through a thin salt stem (Figure 3b). The RTM-based model produces a clearer base of salt and subsalt image than the CBM-based model, confirming that the RTM-derived salt model is more accurate.

RTM with Vector Offset Output (VOO) stacking

Xu, Q. et al. (2011) have proposed a technique to divide the RTM output of each shot into a number of tiles (typically 9) with each tile corresponding to a different vector offset range as measured from the shot location (Figure 4). Instead of stacking the complete apertures of all migrated shots as is done in conventional RTM, each tile is stacked separately across all shots. Given the local geological structure, it is then possible to selectively combine migration outputs from only the vector offsets that contribute to the signal at a given location. This reduces signal contamination by noise from shots not contributing to the illumination of a particular area. Mode-converted waves and multiples that frequently blur the signal near complex salt bodies are also eliminated when they are contributed by a different vector offset than the signal.

Figure 5a shows an RTM image migrated using a salt flood velocity model. In the highlighted region, the base is unclear and difficult to interpret. Local geology indicates that the base of salt at this location must be illuminated mainly by shots to its east. A partial stack that combines only the RTM outputs illuminated from the east (VOO tiles 1, 4 and 7) is shown in Figure 5b. The contribution by shots from other directions, which is almost all noise, is separated from the signal energy near the base of salt at this location. This VOO image of the base of salt is far easier to interpret.

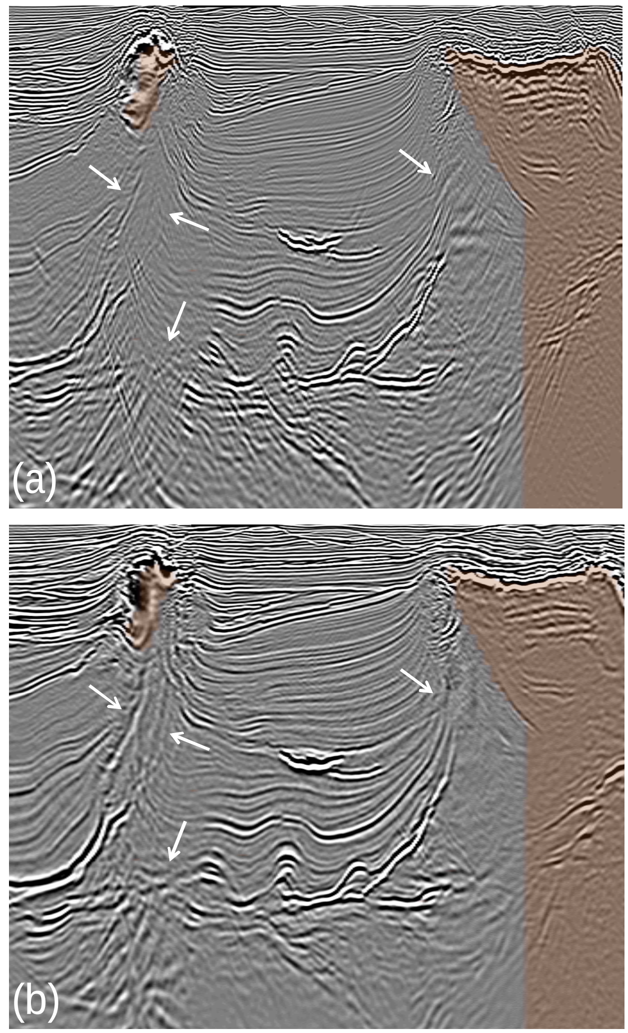

Figure 2: CBM image (top) and RTM image (bottom) migrated with a second sediment flood velocity model – a sediment model with constant salt velocity inserted in the colored sections. RTM produces a much clearer image of the salt structure under the shallow salt defined in this model. Arrows in (b) highlight areas of improved imaging with RTM.

By separating the RTM image into components illuminated from different directions, the partial VOO stacks are a powerful interpretation tool that help create more refined velocity models and a better final image.

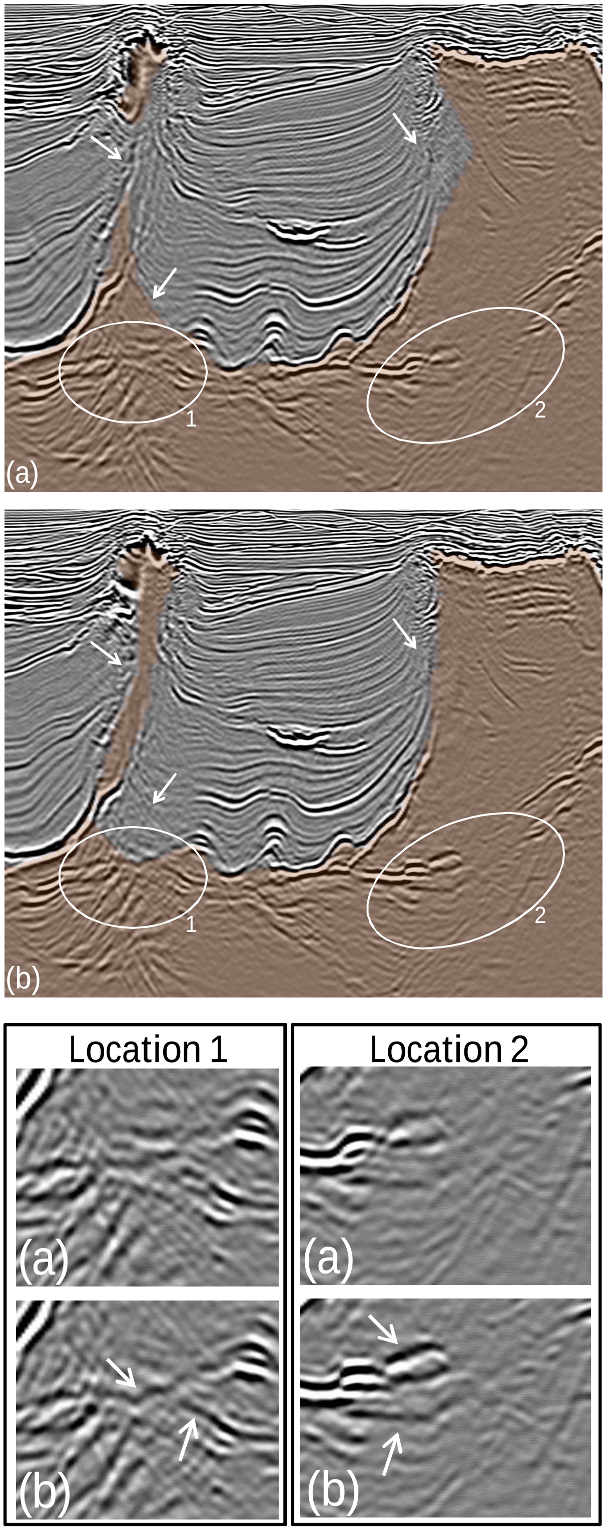

Figure 3: RTM images migrated and overlaid with independent salt interpretations based on the CBM image in Figure 2a (top) and the RTM image in Figure 2b (bottom). The RTM-based interpretation improves the image near the base of salt. Arrows in (a) and (b) indicate key areas where the interpretation is different. Circles highlight improved imaging in (b). Magnified views of the circled locations are shown above.

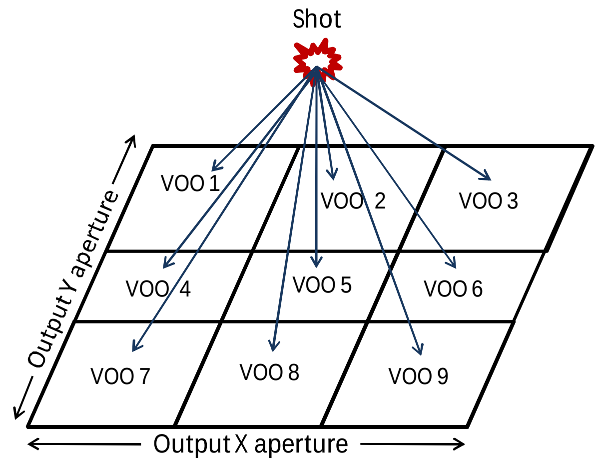

Figure 4: In an advanced application of RTM, the migrated output aperture of each shot is divided into nine tiles each corresponding to a different vector offset output (VOO) (Xu Q. et al., 2011).

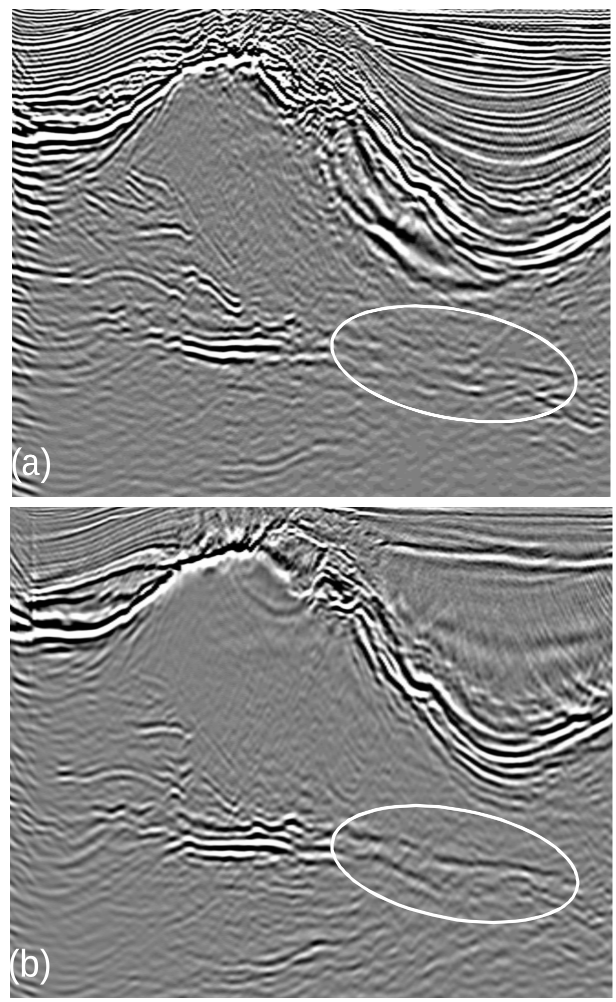

Figure 5: Full RTM stack (top) and partial RTM stack of VOO tiles 1, 4 and 7 (bottom) migrated with a salt flood velocity model. The partial stack produces a cleaner image of the base of salt at this location.

RTM 3D angle gathers for intra-salt tomography

As previously mentioned, the combination of pure halite and evaporite layers in Santos Basin salt introduces velocity variations that can be estimated by intra-salt tomographic inversion. This is usually done using the residual move-out information from common surface-offset gathers provided by ray-based migrations such as CBM. The information provided by such gathers is quite accurate where the salt structures are simple and where continuous bright reflections from evaporite layers are available. In areas where the halite and evaporite layers are mixed or where the salt structure is complex, these gathers are much less reliable. In these places, RTM produces a better image and its gathers should provide better residual move-out information for tomography.

To compare intra-salt tomography from CBM and RTM gathers, a test area of about 400 km^2 containing regions of both layered and mixed salt was selected. The RTM gathers are 3D sub-surface common angle gathers (Xu, S. et al., 2011) that contain both sub-surface azimuth and reflection angle information. They are better suited for wide azimuth (WAZ) surveys, which contain more uniform azimuthal information than NAZ surveys. Since the survey used in these tests is NAZ, the 0º azimuth gathers contained the most information. These 0º azimuth gathers are still more reliable than the commonly used 2D RTM sub-surface angle gathers. 2D RTM gathers are derived by applying the RTM imaging condition at different sub-surface offsets followed by a post-migration conversion to sub-surface angles (Sava and Fomel, 2003). Huang et al. (2010a) showed that these gathers can suffer from smearing artifacts that are detrimental to tomography. The 3D gathers developed by Xu, S. et al. are free from these artifacts since they are obtained directly by decomposing sub-surface wavefields into their local directional components.

Two migrations were applied using the same constant salt velocity model to output CBM surface offset gathers and RTM 3D sub-surface angle gathers. The CBM stack and gathers at a location with a mixture of halite and evaporites in the salt are shown in Figure 6a. Figure 6b shows the corresponding RTM stack and gathers for 0^0 azimuth. The evaporite inclusions and the base of salt are much better defined in the RTM stack which helps the calculation of seismic dips for tomography. The move-out is broken and inconsistent on the CBM gathers while it is clean and consistent on the RTM gathers. In order to discard migration artifacts, the far offsets on the CBM gathers (figure 6a) have been muted near the top of salt. The artifacts are a result of seismic events being focused at multiple depths due to the large velocity contrast near the top of salt (Xu and Huang, 2007). If left unmuted, tomography may attempt to flatten these artifacts. RTM angle gathers are inherently free from such artifacts and do not require muting.

The results of tomographic velocity inversion on the two sets of gathers were equivalent where the salt structure is simple and the salt has continuous evaporite layers. In complex areas, tomography on 3D RTM gathers provided a better velocity update. Figure 7 shows a comparison of intra-salt tomography results in an area where the salt is a mixture of halite and layered evaporites as shown in Figure 7a. Figure 7b, c and d are magnified, 25 Hz RTM images of the base of salt at this location. Figure 7b was migrated with the initial, constant salt velocity model. Figure 7c was migrated with the velocity model from the CBM gather update and is only slightly improved compared to Figure 7b. More improvement is seen in Figure 7d which was migrated with the model from the RTM 3D angle gather update. On this image, the base of salt is more continuous and the sub-salt sediments are more coherent.

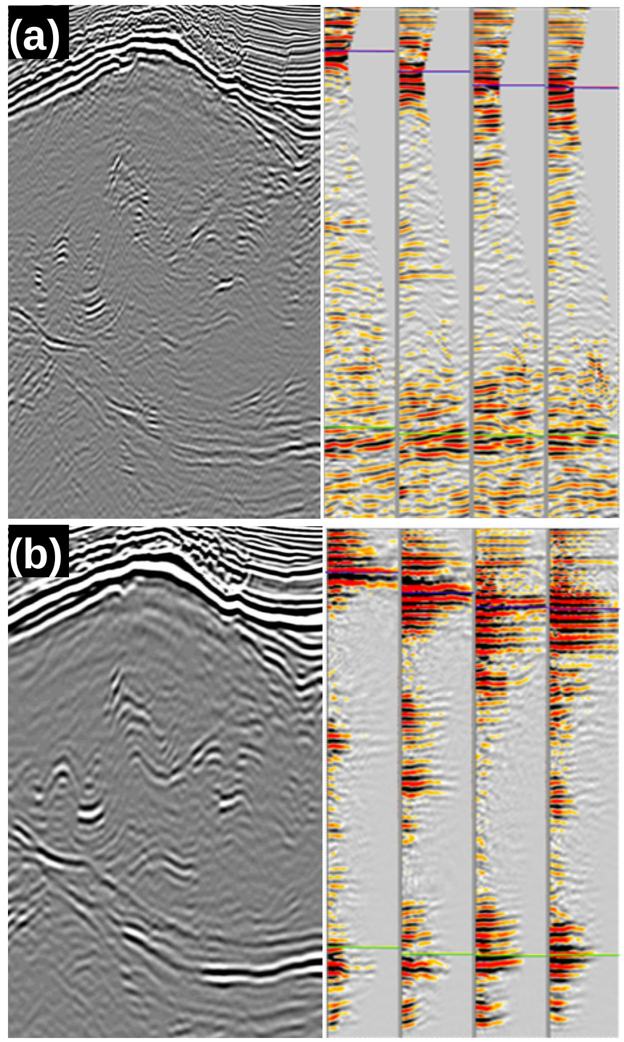

Figure 6: CBM stack and surface offset gathers (top) and RTM stack and 3D angle gathers (bottom) at the same location. The green and blue horizons represent the base of salt shifted down by 200m and the top of salt respectively. The residual move-out on the RTM gathers is more consistent than on the CBM gathers.

This shows that RTM 3D gathers provide high quality residual move-out information, even near areas with complex salt structures or of varying salt composition. Tomographic velocity inversion works better on these gathers than on surface offset CBM gathers. The result is an improved base of salt and sub-salt image.

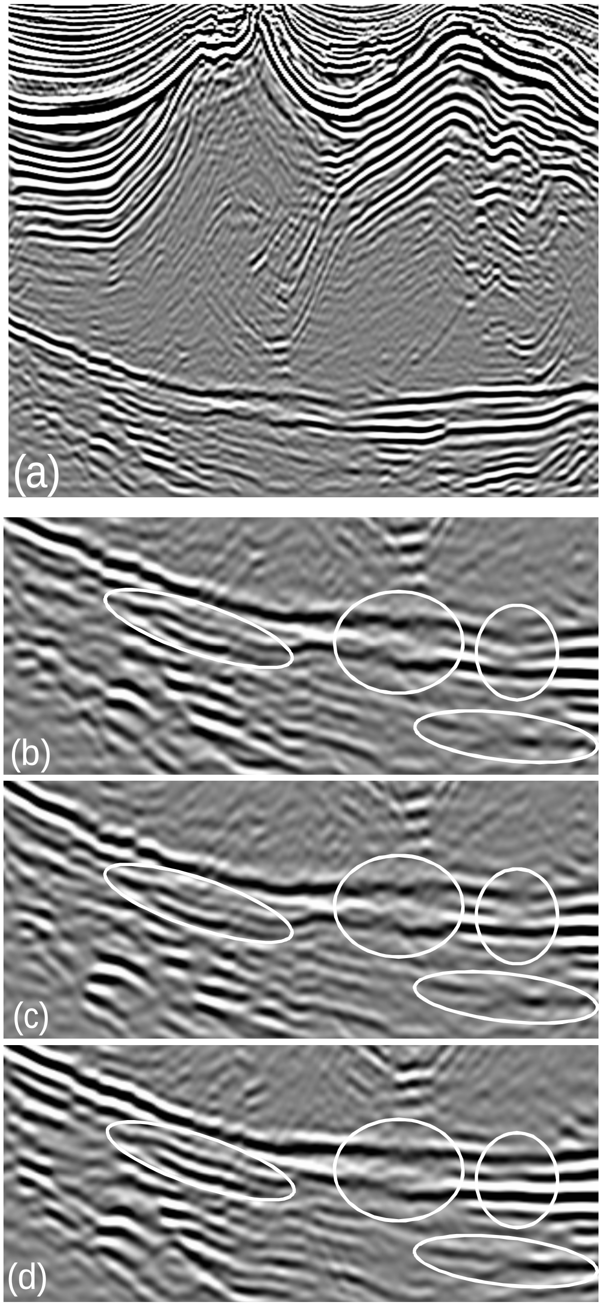

Figure 7: (a) RTM image showing the location of the comparison in (b), (c) and (d). (b), (c) and (d) are magnified RTM images that show the base of salt at this location. They are migrated with a constant salt velocity model in (b), salt velocity from intra-salt tomography on CBM surface offset gathers in (c), and salt velocity from intra-salt tomography on RTM 3D angle gathers in (d). Improvements in the image of base and subsalt events in (d) are highlighted.

Conclusions

Our work demonstrates that, despite the relatively simple geology in the Santos Basin, the accuracy of salt geometry definition and salt velocity can be significantly improved when RTM technology is employed in the model building phase. Compared to ray-based migrations, RTM produces superior images of salt structures which enable a reliable definition of salt geometry. In areas where poor illumination inhibits conclusive interpretation, RTM with selective VOO stacking can improve signal-to-noise ratio and aid interpretation. The information provided by 3D RTM angle gathers for intra-salt tomography ensures a more reliable salt velocity update and an improved image of complex salt. The combined result is a better salt model and, consequently, a better image of the pre-salt target.

References

1. Buur, J., and T. Kuhnel, 2008, Salt interpretation enabled by reverse-time migration: Geophysics, **73**, VE211-VE216.

2. Etgen, J., S. H. Gray, and Y. Zhang, 2009, An overview of depth imaging in exploration geophysics: Geophysics, **74**, WCA5-WCA17.

3. Huang, Y., B. Bai, and T. Huang, 2010, The application of RTM 3D gathers for wide azimuth data in Garden Banks, Gulf of Mexico: 80th Annual International Meeting, SEG, Expanded Abstracts, 3298-3302.

4. Huang, Y., D. Lin, B. Bai, S. Roby, and C. Ricardez, 2010, Challenges in pre-salt depth imaging of the deepwater Santos Basin, Brazil: The Leading Edge, **29**, no. 7, 820-825.

5. Reasnor, D. M., 2007, Salt interpretation practices for depth imaging in the Gulf of Mexico: The Leading Edge, **26**, no. 11, 1438 -1441.

6. Sava, P., and S. Fomel, 2003, Angle-domain common-image gathers by wave field continuation methods: Geophysics, **68**, 1065-1074.

7. Xu, Q., Y. Li, X. Yu, and Y. Huang, 2011, Reverse time migration using vector offset output to improve subsalt imaging – A case study at the Walker ridge GOM: 73rd Annual International Meeting, EAGE, Expanded Abstracts.

8. Xu, S., and T. Huang, 2007, Migration artifacts and velocity analysis: 77th Annual International Meeting, SEG, Expanded Abstracts, 3019-3023.

9. Xu, S., Y. Zhang, and T. Bing, 2011, 3D angle gathers from reverse time migration: Geophysics, **76**, 77-92.

10. Zhang, Y., and J. Sun, 2009, Practical issues in reverse time migration: true amplitude gathers, noise removal and harmonic source encoding: First Break, **26**, 29-35.

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