Velocity Update Using High Resolution Tomography in Santos Basin, Brazil

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Abstract

The exploration interest in the Santos Basin offshore Brazil has increased with the large deep water pre-salt discoveries, such as Tupi and Jupiter. As the overburden of reservoir has complex structures in the Santos Basin, a reliable seismic image in depth domain is critical to exploration success in this region. In order to obtain a high quality seismic image, an accurate velocity model is crucial. With implementation of high resolution tomography algorithms, smaller scale velocity details are able to be captured in seismic surveys with complex structures. Here we present an application of high resolution tomography for velocity update in the Santos Basin, which resulted in improved supra-salt and pre-salt images after depth migration. We also discuss the possibility of using Reverse Time Migration (RTM) 3D angle gather for model building in this area.

Introduction

Located in the South Atlantic Ocean, the Santos Basin is one of the largest Brazilian sedimentary basins and also the site of several significant oil discovery in the past five years (2006 ~ 2010). These include Tupi, Bem-te-vi, Carioca, Parati, Caramba and Jupiter. Most recently, BG Group PLC, an integrated oil company, announced a new oil discovery of approximately 26 API in Block BM-S-10 in February, 2011.

Most oil discoveries in the Santos Basin occurred in the pre-salt layer, which is a geological formation on the continental shelves off the coast of Africa and Brazil. Drilling through sediments and salt to extract the pre-salt oil and gas is expensive and risky. A good seismic image is important for accurate subsurface structures interpretation. However, several geological and geophysical challenges remain in this region, such as obtaining a precise velocity model and accurate salt interpretation.

Layer-constrained tomography, iterative salt interpretation and intra-salt tomography have been demonstrated to improve the pre-salt image in Santos Basin (Huang et al., 2010). However, distortions within sediment layers, evaporites and pre-salt layers can still be observed in depth images. Numerous tests illustrate that one reason for these distortions is the inaccuracy of the velocity model. Compared to the real velocity field, the velocity model from conventional model building workflow is accurate only on low frequency part; but the small scale details, which is the high frequency part of the model are missing. For the areas with or beneath a high lateral or vertical velocity contrast (e.g. gas pocket, shale, salt, carbonate, etc), these complex geological bodies cannot be properly imaged without including the detailed rapid variations in the velocity model.

In this paper, we first discuss the workflow and key issues in performing high resolution tomography. Then use a narrow azimuth dataset around the Tupi well in Santos Basin to demonstrate that a more accurate tomographic velocity model and a resulting improved depth migration image achieved from the proposed flow. Ray-based Controlled Beam Migration (CBM) is used in this study for generating depth images and Common Image Gathers (CIGs). At the end, we discuss the benefit of RTM 3D angle gathers and explore the possibility of using angle domain tomography for high resolution tomography in Santos Basin.

Data For Study

In our first high resolution tomography application, the dataset was from a narrow azimuth survey acquired from BM-S-11 block around the Tupi field in Santos Basin, Brazil. The acquisition direction is east-west. Streamer length is 6 km. Initial velocity is an isotropic velocity model generated after several iterations of conventional sediment tomography, salt interpretation, intra-salt and pre-salt tomography updates. The velocity model grid is 75mx75mx50m. A pre-stack depth CBM was used to create surface offset Common Image Gathers (CIGs) since it gives cleaner images than Kirchhoff migration (Ting and Wang, 2009). The data was migrated up to 35 Hz.

High Resolution Tomography

A standard flow for tomography is described in Figure 1. There are several factors affecting the resolution of the tomographic inversion. In this paper, we mainly demonstrate the high resolution tomography achieved by high-quality dense event picking, fine grid inversion and mild model smoothing.

High-quality event picking is essential for high resolution tomography to make the inversion stable and converging. An automatic picking scheme is used to pick the residual curvature on CIGs and the reflector dipping information on the stack. The picking criteria such as reflector coherency, minimum spacing between picked events, and average semblance and amplitude level of CIGs were adjusted to ensure that only reliable events were picked (Liu and Han, 2010).

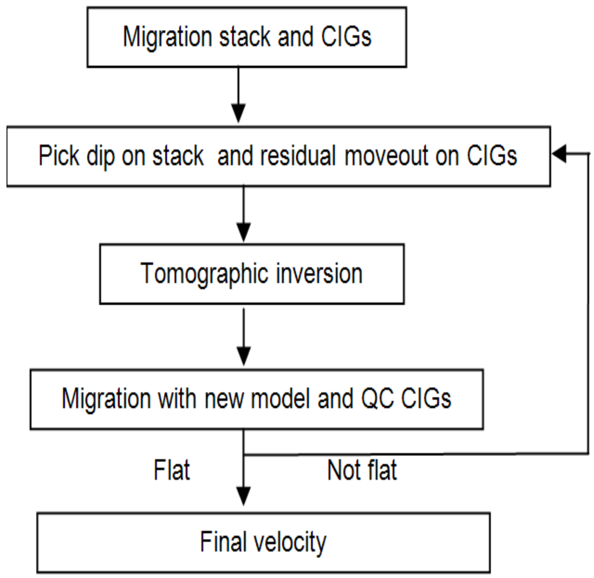

Figure 1. Standard tomography flow

The key to upgrading conventional tomography to high resolution tomography is to increase the density of the event picking in x, y and z directions. Residual curvature-based tomography solves a linear system of equations (Zhou et al., 2003). There are a limited number of unknowns (the velocity at each grid), and each picked event generates an equation as a known condition. The more high-quality events are picked the more consistent conditions can be applied to the inversion. In our workflow, the CIGs grid used for picking is 75mx75m. Compared to the grid of 225mx225m used in the conventional tomography workflow to generate the reference velocity, the number of CIGs used for event picking is nine times more. Furthermore, the minimum event separation along z direction is reduced to 30m from 200m. The denser event picking in all three dimensions (x, y and z) dramatically increased the number of picks, and thus the size of the matrix in the tomographic inversion.

Though high velocity resolution can be reached with a coarser inversion solver by combining with a finer ray-tracing grid (Jones 2010), the finer inversion grid still produces better result as long as the computation power allows. In our case, the inversion grid is set to be the same as the velocity grid, i.e. 75mx75mx50m. In addition, the smoothing size in the tomography is also reduced to retain the high resolution in the updated model. Overall, the high-resolution tomography scheme features velocity updates at a fine scale which cannot be achieved in a conventional tomography. The price paid for this workflow is increased computational cost, but it is available in practice with parallel computing by increasing the number of CPUs and the size of memory.

Application to geological body at shallow sediment

Figure 2A shows the initial velocity overlaid with the CBM full stacked image at shallow sediment. Two geological bodies can be observed on the seismic image at around 600m below water bottom (indicated by circles), but they are difficult to identify on the initial velocity model. Figure 2C shows the gathers extracted from the geo-body on the left. The downward curvature on the CIGs indicates that the initial velocity was too fast. These two geo-bodies can be gas pockets as gas hydrates are often revealed as strong reflectors with low velocity anomalies. Figure 2B and 2D show the velocity and CIGs after the high resolution tomography update. The two possible gas pockets can easily be identified on the updated velocity model and the low velocity zones match the structures on the stack. The CIGs are also flatter, indicating a more accurate velocity model is obtained.

Application to intra-salt velocity update

Figure 3 shows the CBM gathers extracted from an evaporite layer. The two events indicated by the arrows in Figure 3A reveal a conflict: the top event curves down, indicating a slower velocity is needed; the bottom event curves up, indicating a faster velocity is needed. This is a common dilemma seen in velocity model update. By using conventional tomography, correcting one event sometimes leads to a degradation of the other. With high resolution tomography, the velocity update is more localized and flexible to catch this rapid vertical velocity change. Figure 3B shows the CBM gathers migrated with the velocity after high resolution tomography. Both events are flatter and better focused.

Application to improvement of sub-salt image

High resolution tomography is usually applied only in shallow regions for two reasons: complex geological anomalies (e.g. gas pocket, carapace and carbonate etc) and wide reflection angles. In some areas, the geology in deep areas, especially sub-salt, is relatively smooth, making high resolution unnecessary. However, this is not the case for Santos Basin. Santos Basin features a deep pre-salt layer with significant velocity variation and many deep faults. Using a smooth velocity model may distort these geological features. Figure 4 shows a comparison of a CBM full stacked image migrated using the initial velocity model (Figure 4A) and the high resolution tomography-updated velocity (Figure 4B). Figure 4B shows improved coherency at pre-salt events and focus at deep faults.

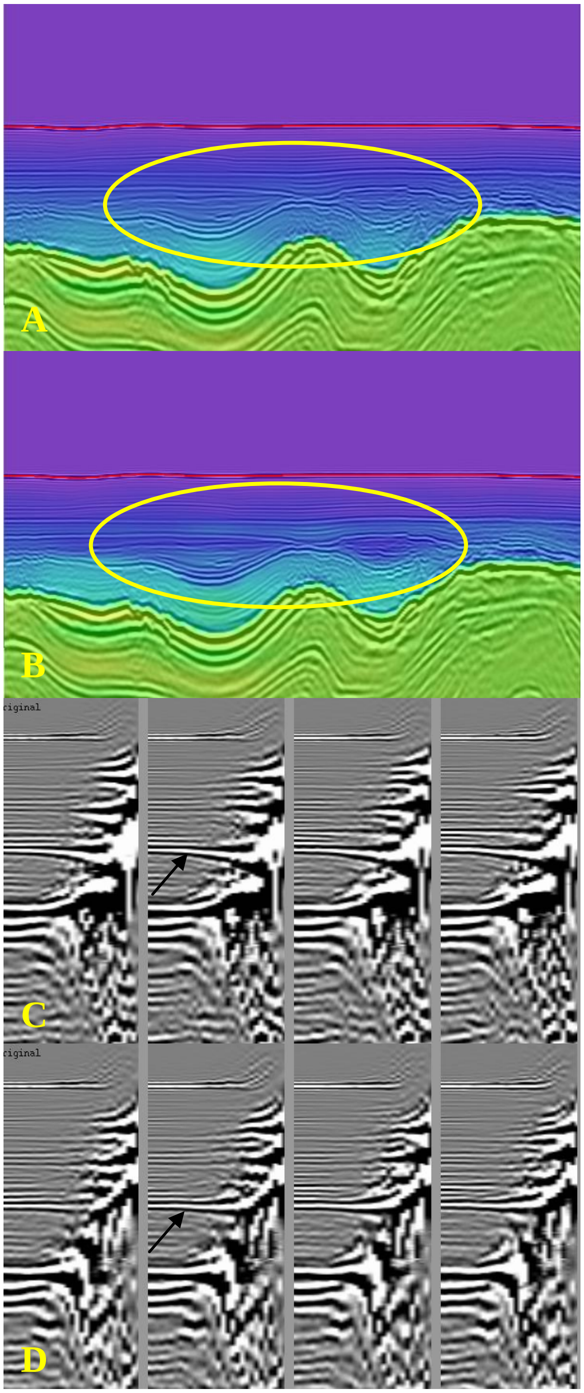

Figure 2: A) The Initial velocity (Geo-body cannot be identified); B) The updated velocity (Geo-bodies can easily be identified); C) CBM gathers with intiial velocity (Curves down) ; D) CBM gathers with updated velocity (Flat)

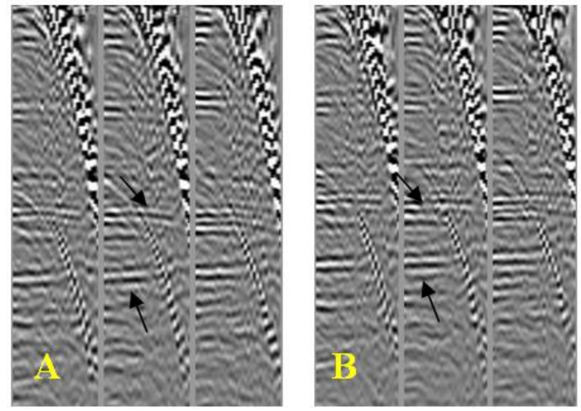

Figure 3:A) CBM gathers with initial velocity (top event curves down and bottom event curves up); B) CBM gathers with updated velocity (Both events are flat)

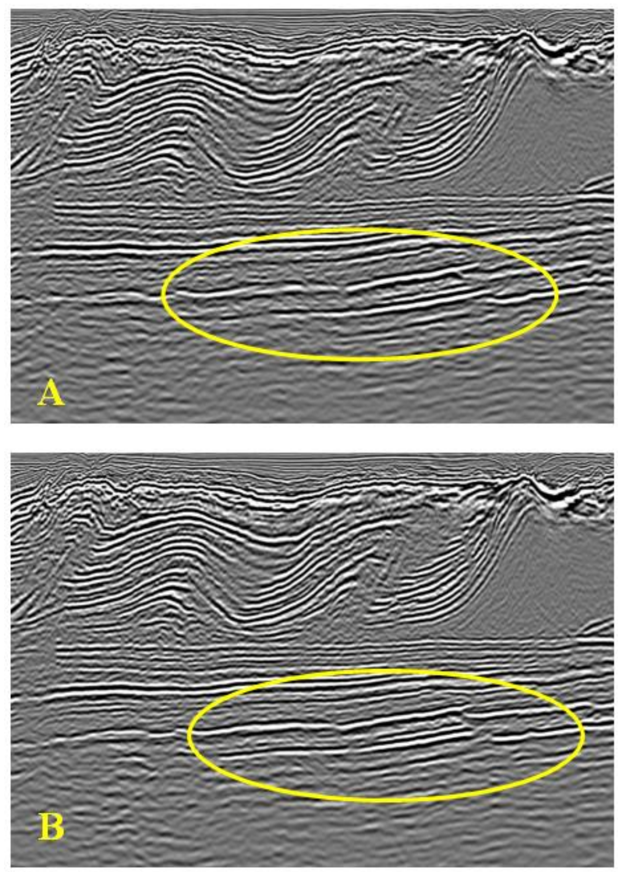

Figure 4: A) CBM full stack with the initial velocity; B) CBM full stack with updated velocity (Better coherency at pre-salt events and deep faults)

Discussion

The tomography using CIGs in offset domain has limitations. When the velocity model is complex, the CIGs in offset domain not only contain migration artifacts (Nolan and Symes, 1996), but also are proven more difficult to stabilize the implementation in tomography (Zhang et al., 2010). RTM 3D angle gathers suffer much less migration artifacts, and the tomographic inversion could be approximately to a local update, thus it yields a better subsalt tomography velocity update (Xu et al., 2011; Huang et al., 2010b). In addition, RTM takes care of rapid spatial velocity variations much better than beam migration, and can image more complex geology structures. In Santos Basin, more continuous base of salt (BOS) and pre-salt layers are imaged with RTM in the areas below rugose top of salt (TOS) (Huang et al., 2010). In these areas, we expect RTM angle gathers to provide better event continuity, thus improving the quality of event picking for tomographic inversion.

Figure 5C is a CBM full stack at a pre-salt layer after high resolution tomography using CBM CIGs and the distortion can still be observed as indicated by circle. Figure 5A and 5B show offset domain and angle domain CIGs produced by CBM and RTM, respectively. The gathers are extracted from the location indicated by the arrow in Figure 5C. As expected, both CIGs gave good events at simple geology area, but RTM 3D angle gathers (Figure 5B) show better continuity at the area with distortion. The coherent events in the CIGs would lead to high quality event picking for tomographic inversion. Based on the comparison of CIGs, velocity model was further updated using RTM 3D angle gathers on an inversion grid of 150x150m. Figure 5D shows the CBM full stack migrated with the updated model using RTM 3D angle gathers. Compared to Figure 5C, the events at circled area are more coherent. Based on above results, it is promising to use RTM 3D angle gathers in high resolution tomographic inversion for Santos Basin model building. More tests will be carried out in future.

Conclusions

In this paper, we presented a high resolution tomography application in deep water Santos Basin. With high resolution tomography for velocity update, shallow velocity anomalies can be easily identified and the intra-salt and subsalt images are more coherent and focused. RTM angle gathers can be incorporated to further improve the velocity model building.

Acknowledgements

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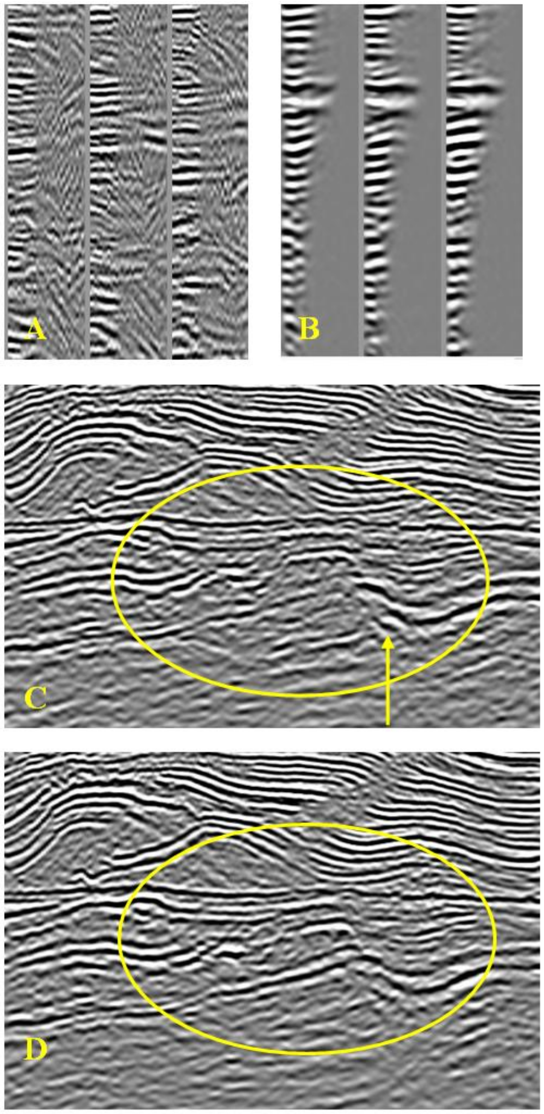

Figure 5: A) CBM CIGs in common offset domain; B) RTM 3D angle gathers; C) CBM full stack with updated velocity using CBM CIGs for tomography; D) CBM full stack with updated velocity using RTM 3D angle gathers for tomography

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