Pre-salt imaging improvements with variable-depth streamer data in the Santos Basin

*Jeremy Langlois, Bing Bai, Yan Huang (CGG)

Abstract

Recent discoveries in pre-salt areas of Brazil's Santos Basin have stimulated momentum for producing higher resolution images of the region's geologically complex structures. Variable-depth streamer acquisition is an emerging technology that can improve the usable bandwidth in both the low- and high-frequency ranges, reduce sea-state-related noise, and improve low frequency penetration into the deep pre-salt targets. Additionally, we examine its advantages for producing higher-resolution velocity models. We use two real field data sets, one acquired with flat and one with variable-depth streamers, to demonstrate the improvements to pre-salt imaging in the region with variable-depth streamer data.

Introduction

In industry-wide efforts to improve imaging in geologically complex regions around the world, unconventional acquisition configurations designed to acquire data with broader bandwidth are drawing much attention. One such configuration involves variable-depth streamers designed to create notch diversity, thereby increasing the usable bandwidth of the recorded seismic data (Soubaras, 2010). In addition, because most sections of each streamer are towed much deeper than conventional flat streamers, the acquisition configuration also add two additional benefits to the seismic data: 1) it avoids much sea-state-related noise, thus improving the overall signal to noise ratio (S/N), and 2) the frequency band has a much sharper notch at zero frequency; this additional low frequency may be particularly beneficial for the pre-salt imaging. With typical earth attenuation, the low frequency signal has a better chance to reach the pre-salt and be recorded in the seismic acquisition. The variable-depth streamer acquisition can create a broader amplitude spectrum while increasing the S/N, especially in low frequency as compared to conventional flat-streamer acquisition. When coupled with advanced imaging techniques, we can obtain improved images, even beneath complex salt structures.

Because of the impressive pre-salt discoveries in recent years, demand is growing for high-resolution images of the region. We endeavor to test the variable-depth streamer configuration in Brazil's Santos Basin. Yet, due to the Santos Basin's geologic complexity, designing workflows for imaging the region's deep pre-salt targets can be challenging. We endeavor to overcome the difficulties in both the pre-processing and velocity model building.

The improved S/N ratio and low-frequency response of the new acquisition may help us image deep beneath the salt. In order to fully utilize the potential of the variable-depth streamer data, we need to preserve the wide spectrum character of the data and handle the ghost properly – both in preprocessing and final imaging. For variable-depth streamer data, Lin et al proposed a processing flow (2011), Sablon discussed a multiple attenuation method (2011), and Langlois proposed a simplified flow for deghosting and demultiple (2013). We adopted the simplified flow in this study.

Obtaining an accurate velocity model is critical for correctly imaging the subsurface. Huang et al. (2010) designed a detailed workflow for model building in the Santos Basin and implemented an iterative approach to salt interpretation. The results showed an improvement in the top of salt (TOS) and base of salt (BOS) reflections and, subsequently, a superior pre-salt image. We extended the flow on the variable-depth streamer data set, focusing on improvements to the pre-salt image in the Santos Basin.

In following sections, we demonstrate the benefit of the variable-depth streamer data on high S/N, especially low frequency. We briefly introduce the pre-processing flow, then focus on the velocity model building in Santos Basin to demonstrate the benefit of 1) a TTI model over an isotropic model. 2) high resolution tomography, 3) iterative model updates. We finally compare our preliminary results using variable-depth streamer data to an existing conventional, flat-tow acquisition data set acquired in a couple of years earlier.

Improved Signal Content

In variable-depth streamer acquisition, the cable depth follows a survey-specific profile that is shallower at the near channels and deeper towards the far channels. Simply because of this deeper tow that avoids much sea-state-related noise, we benefit automatically from a higher signal-to-noise ratio (S/N) in the data. For our study, our variable-depth streamer acquisition has near channels towed as shallow as 10 m and far channels as deep as 50 m. The variations in cable depth create a diverse ghost response that is unattainable using conventional flat-streamer acquisition. With the deeper-than-conventional acquisition towing cables, more low-frequency signal is preserved. Additionally, the notch diversity, due to the variable-depth streamer, provides a better chance to broaden the spectrum. The decrease in acquisition-related noises and the increase in low frequency signal improve the S/N, especially at lower frequencies; this is particularly beneficial for pre-salt imaging. Figure 1 compares common channel gathers of both conventional and variable-depth streamer acquisition. In the variable-depth streamer data, we can observe a clear noise reduction, particularly in the deeper channels, as well as improved event coherency below the salt, likely due to the improved low frequency response.

Soubaras explained the benefits of notch diversity created by varying acquisition cable depths from near channels to far and gave an example of a post-migration joint deconvolution deghosting method that suppresses residual ghost energy (2010). A “bootstrap” methodology was introduced in 2012 in order to suppress ghost energy from pre-migrated shot gathers (Wang and Peng, 2012). We implement this pre-migration bootstrap approach.

We implement a simplified SRME flow (Langlois 2013) for variable-depth streamer acquisition by deghosting the data prior to multiple prediction and then adaptively subtracting the ghost-free multiple from the ghost-free data, allowing for improved turnaround time and for additional model updates.

Velocity Model Building

Regardless of the acquisition design, i.e. constant- or variable-depth streamers, velocity model building in the Santos Basin can be a challenge due to the deep pre-salt targets and complex salt bodies above them. With this variable-depth streamer data, an isotropic salt flood velocity model is derived previously for fast track work. It is built initially using velocity trends found in neighboring areas as well as a handful of shallow wells and followed by several iterations of sediment tomography. The TOS interpretation is done in a coarse grid (Langlois 2013).

For this study, we derive a preliminary Transverse Tilted Isotropy (TTI) velocity model that utilizes well information available in the region. The rich bandwidth associated with variable-depth streamer acquisition reveals finer geologic details, thereby assisting interpretation of events – both sediment and salt. The high resolution offers more precise information in common image gathers and improves sediment tomography; shallow faults are also better defined.

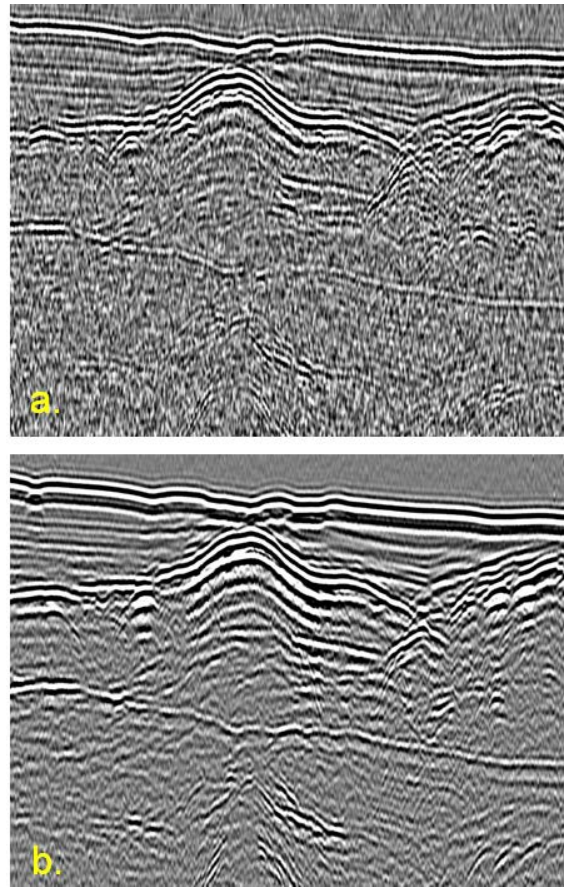

Figure 1: A mid channel for conventional and variable-depth acquisition is shown prior to SRME, 1a and 1b respectively. A 10Hz high-cut filter has been applied to each. In the variable-depth acquisition section, we can see increased coherency throughout and reduced sea-state related noise related to deeper acquisition tow. The receiver depth is approximately 9m for the conventional and 29m for the variable-depth acquisition.

We perform high-resolution tomography around several shallow well locations in order to derive a more accurate sediment model. The results show that with the improved resolution on the data, along with high-resolution tomography, detailed velocity contrasts can be derived from the seismic data. These velocity inversions tie seismic events very accurately to the well markers and, at the same time, provide more information on the geologic properties of the surrounding areas. More accurate models can provide increased confidence when investigating potential targets, especially in highly fractured areas with complex velocity fields. Figure 2 demonstrates the improvements seen with high-resolution tomography on broadband data. The higher frequency gathers allow for a more accurate velocity model in a highly fractured section. Well information confirms the velocity inversion at this location. Figure 3 shows an interpretation of the oil/water contact. We can see the improved continuity and structural improvements between the fast-track isotropic model and the new TTI velocity in the area. We are able to tie several well markers in the region at the oil/water contact and to the top of the Cretaceous.

The broadened spectrum enables us to perform a more detailed update in the Albian region and obtain a better TOS image. TOS and BOS are interpreted on the sediment flood and salt flood volumes, respectively. We build a preliminary salt model and perform a TTI Controlled Beam Migration using the salt model. The results show further improvement to the pre-salt structure. Figure 4 shows a comparison of the preliminary TTI updated migration and the fast-track isotropic migration; it illustrates enhancements in the pre-salt image.

After going through the top-down model building and obtaining a reasonable pre-salt image, mainly based on pre-salt image, additional scenarios are performed to further improve the velocity model in both overburden sediment velocity and salt geometry. We observed that the pre-salt image response sometimes can be a good source for judging the accuracy of the overburden velocity model. The iterative velocity model updates show benefits to obtain a better pre-salt image.

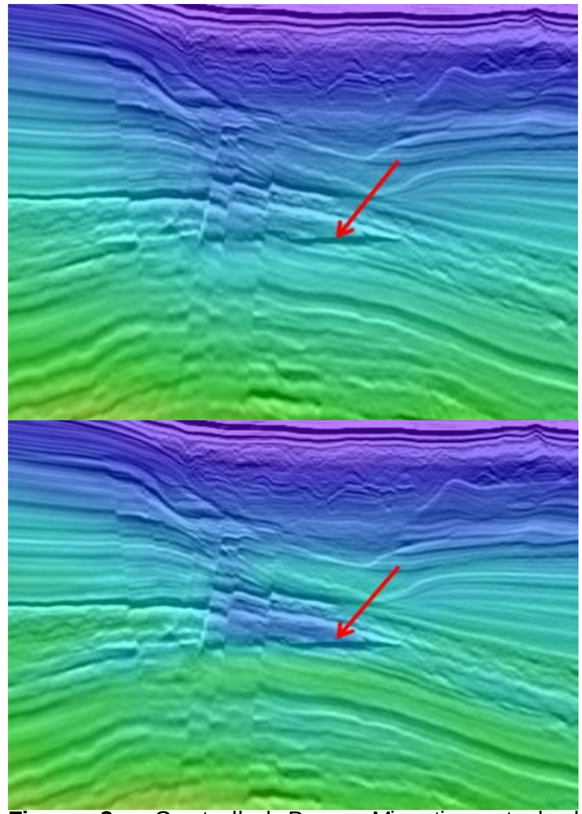

Figure 2: Controlled Beam Migration stacked images are used to demonstrate the improved layering of the model updates related to high-resolution tomography. Broadened bandwidth helps add detail to the model. The red arrow points to the oil/water contact with mis-ties varying from 3-5 m in the sediment flood volume.

Image comparison of conventional data and variable depth streamer data

We use the preliminary TTI velocity model in a region which overlaps an existing conventional acquisition survey acquired recently. Kirchhoff PSDM is used for both the conventional streamer acquisition and the variable-depth streamer acquisition.

Even the variable-depth streamer data is a preliminary result, it still shows benefits when compared to the final result from the conventional data. A comparison is showed in Figure 5. More continuous and stronger BOS and pre-salt events are imaged with the variable-depth streamer data (Figure 5b) when compared to the conventional flat streamer results (Figure 5a). The improved signal content in the pre-salt, especially the low frequencies, could be related to higher S/N ratio and better low frequency penetration provided by the deeper streamer depth in the variable depth streamer data. Also, higher resolution and less side lobes can be seen in the shallow sections above salt in Figure 5d (variable-depth streamer) when compared to Figure 5c (conventional flat streamer). The better image can leading to a more accurate interpretation and, potentially, an improved velocity model.

Conclusions

Variable-depth streamer acquisition provides highly notch diversified, stronger low frequency penetration and less see-state-related noise contaminated broadband seismic data. In this paper we use an imaging flow designed for utilizing the variable-depth streamer data to obtain improved pre-salt images. The flow includes bootstrap deghosting, 3D SRME in pre-processing and TTI model building with high resolution tomography, salt geometry interpretation and iterative model updates. The resulting images contains higher resolution sedimentary beddings, less side lobe interference, better defined salt delineation and clearer pre-salt structure when compared to images with conventional flat streamer data conventional data. A more detailed processing and further velocity updated are planned for the future work.

Acknowledgments

We would like to thank CGG for permission to show these results. We would like to thank Nicolas Chazalnoel and Ferudun Kilic for their feedback and assistance.

References

Dowle, R., 2006, Solid streamer noise reduction principles: 76th Annual International Meeting, SEG: Expanded Abstracts, 85-89

Huang, Y., D. Lin, B. Bai, S. Roby, and C. Ricardez, 2010, Challenges in presalt depth imaging of the deepwater Santos Basin, Brazil: The Leading Edge, 29, 820–825.

Langlois, J, B. Bai, and Y. Huang 2013, Challenges of pre-salt imaging in Brazil's Santos Basin: a case study on variable-depth streamer dataset, EAGE accepted

Lin, D., R. Sablon, Y. Gao, D. Russier, D. Hardouin, B. Gratacos, R. Soubaras, and P. Whiting, 2011, Optimizing the processing flow for variable-depth streamer data: First Break, 29, 89–95.

Sablon, R., D. Russier, O. Zurita, D. Hardouin, B. Gratacos, R. Soubaras, and D. Lin, 2011, Multiple attenuation for variable-depth streamer data: From deep to shallow water: 81st Annual International Meeting, SEG: Expanded Abstracts, 3505-3509.

Soubaras, R., 2010, Deghosting by joint deconvolution of a migration and a mirror migration: 80th Annual Internatinoal Meeting, SEG: Expanded Abstracts, 3406-3410.

Wang, P. and C. Peng, 2012, Premigration deghosting for marine towed streamer data using a bootstrap approach: 82nd Annual International Meeting, SEG: Expanded Abstracts, doi: 10.1190/segam2012-1146.1.

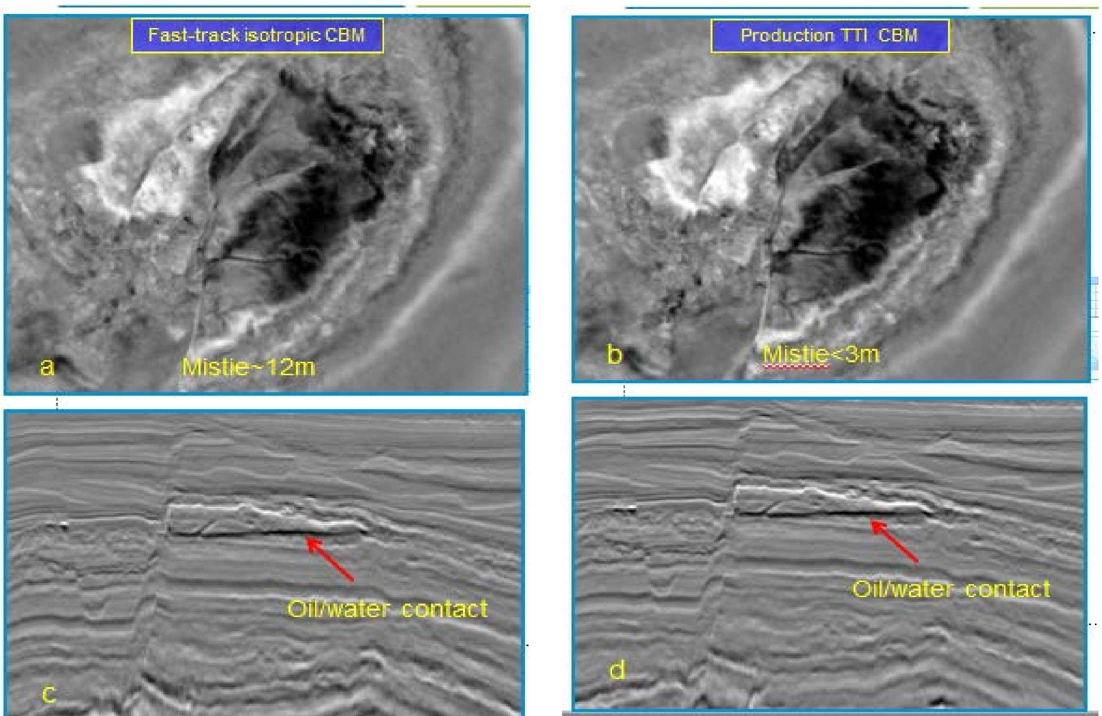

Figure 3: A Controlled Beam Migration is used to show benefits of the production TTI velocity updates. Well markers indicate misties between 12-15 m for the isotropic model, and within 3 m for the TTI model and can be seen in the depth slices for isotropic and TTI in figures 3a and 3b respectively. The oil/water contact is also significantly flatter in the TTI model update shown in figures 3c and 3d.

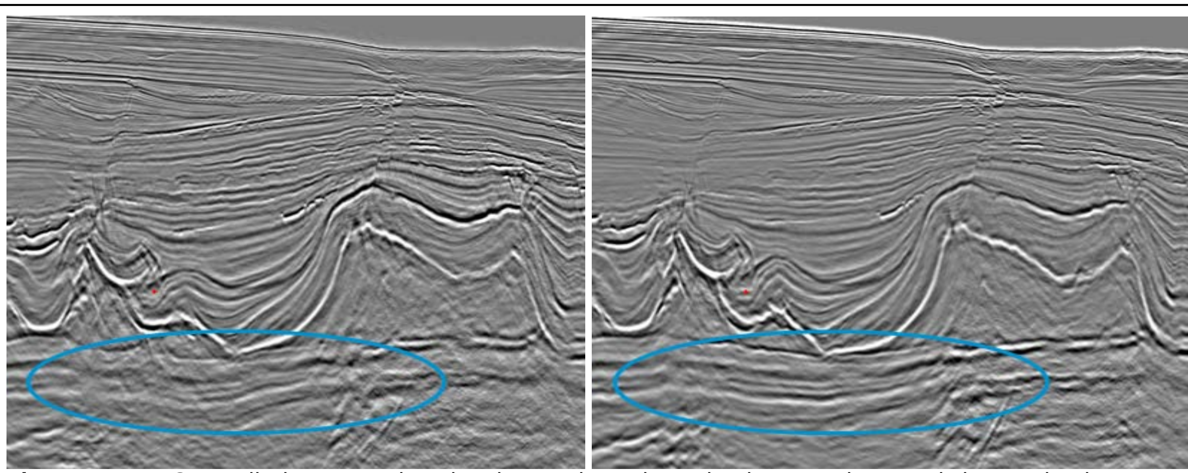

Figure 4: A Controlled Beam Migration is used to show the improved pre-salt image in the pre-salt section after high-resolution TTI tomography. The image on the left is the fast-track isotropic image. On the right is a preliminary TTI result.

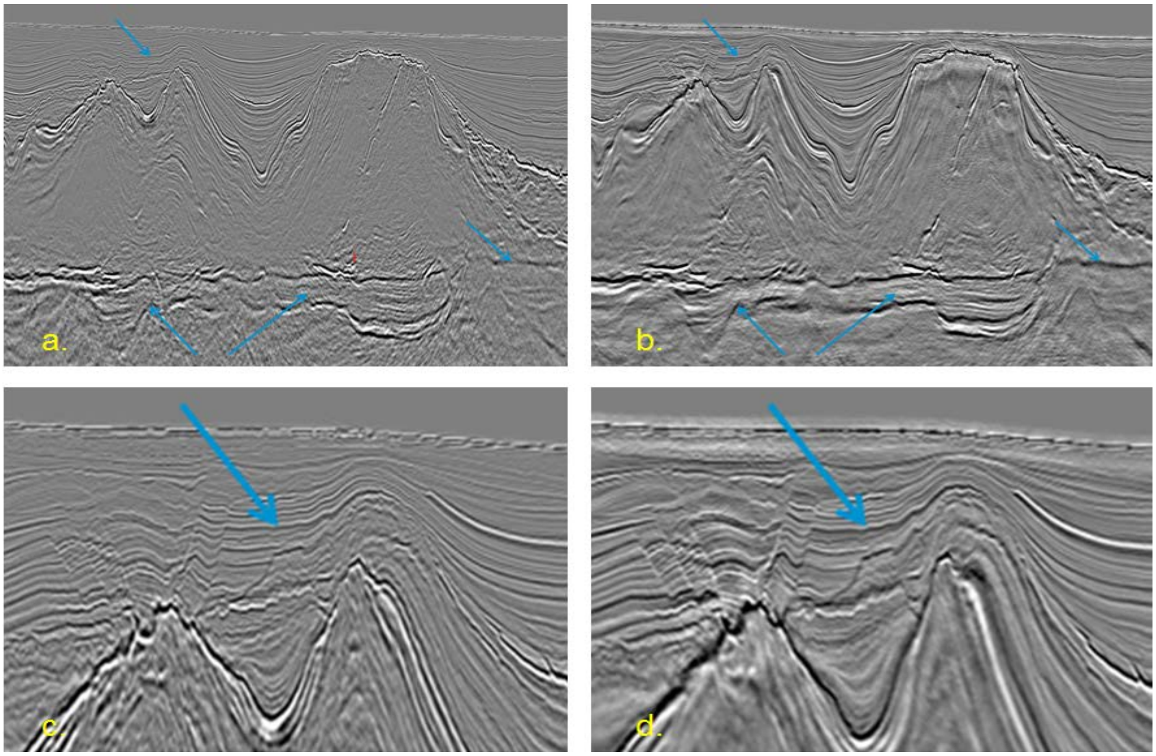

Figure 5: A comparison of a conventional acquisition and variable-depth acquisition is shown in Figures 5a and 5b respectively. We can see improved pre-salt resolution and focusing at the BOS. A zoomed section is shown in Figures 5c and 5d. Notice the improved definition of the faults and reduction of side lobes at the top of salt.