Challenges of pre-salt imaging in Brazil’s Santos Basin: A case study on a variable-depth streamer data set
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Summary

Recent offshore discoveries in the Santos Basin have drawn attention to pre-salt targets; however, seismic imaging in the Santos Basin has proven to be challenging due to the complex geology and deep pre-salt targets. Variable-depth streamer acquisition is an emerging technology that provides opportunities to increase the usable bandwidth in both the low and high frequency ranges, gain stronger low frequency penetration, and reduce acquisition related noise. However, this new acquisition poses additional challenges to seismic processing, creating a need for new processing technologies and work flows. To overcome both the geological and acquisition-related challenges, we modify the processing work flow, then utilize a real field data set of variable-depth streamer acquisition to demonstrate that variable-depth acquisition combined with advanced processing techniques is beneficial to pre-salt imaging in the Santos Basin.
Introduction

Much attention has been given to Brazil’s Santos Basin in recent years because of the impressive discoveries in the pre-salt region. Yet because of the geologic complexity of the region, designing workflows to produce accurate images of the deep, pre-salt targets can be difficult. In industry-wide efforts to improve imaging in complex regions like the Santos Basin, we have recently seen a surge of unconventional acquisition configurations designed to acquire data with broader bandwidth. One such configuration involves variable-depth streamers designed to create notch diversity, thereby increasing the bandwidth of the recorded seismic data. Because of the richer low-frequency content, which has stronger penetration into deep pre-salt targets, variable-depth streamer acquisition is an appealing experiment for the Santos Basin region.

However, the utilization of variable-depth streamer data in the Santos Basin region creates additional challenges for data processing. In addition to the geologic complexities that often require customized workflows with even conventional, flat-streamer data, a workflow with variable-depth streamer data needs adaptation to handle and fully utilize the increased bandwidth. Huang et al. (2010) designed a detailed workflow for model building in the Santos Basin, and implemented a top down approach, using several horizons and an iterative approach to salt interpretation. The results showed an improvement in the top of salt (TOS) and base of salt (BOS) reflections and a better pre-salt image. We look to implement this model building approach on a variable-depth streamer data set, focusing on modifications to 3D SRME and deghosting, while looking to improve the turn-around time for a fast-track volume and provide improved resolution at the pre-salt level.

Processing for 3D Variable-depth Streamer Data

Unlike conventional marine streamer acquisition, the variable-depth streamer does not have a constant cable depth; instead, the cable depth follows a survey-specific profile that is generally shallower at the near channels and deeper towards the far channels. Due to the differences in data associated with variable-depth streamers, the conventional processing flow needs to be modified to better serve it. The key elements of the modifications are as follows: maintaining the full bandwidth in the data, improving variable-depth streamer SRME, and deghosting the imaging gathers for velocity updates (Lin et al. 2011). The variations in cable depth create a diverse ghost response, requiring modifications for both SRME and velocity model building. Naturally, deghosting is a major focus when processing variable-depth streamer data. In this paper, we propose a simplified approach to Lin’s variable-depth streamer data processing flow in SRME and model building by utilizing bootstrap pre-migration deghosting.

Soubaras explains the benefits of notch diversity created by variations in receiver depth from near channels to far and gives an example of a post-migration joint deconvolution deghosting method that suppresses residual ghost energy (Soubaras 2010). A “bootstrap” methodology was introduced in 2012 in order to suppress ghost energy from pre-migrated shot gathers (Wang and Peng, 2012).

Wang and Peng’s proposal has been shown useful for both variable-depth streamer data and conventional data. The method utilizes a mirror dataset generated from 1D ray tracing, and jointly inverts for the receiver-ghost-free data, refining the deghost filter iteratively by minimizing a cost function in the pre-migration stage. It derives ghost delays from data optimization allowing for limited impact from receiver or shot depth errors. Accurate angle estimation is not required with this method; thus, it is viable for both 2D and 3D data regardless of sparse sampling of shots and receivers.

The receiver ghost associated with variable-depth streamer acquisition can be seen on migrated gathers as an event with reversed polarity trailing the primary event (Figure 1a). The separation between the ghost event and the primary event becomes greater with offset due to differences in both travel time and receiver depth. The ghosts in the gather can interfere with the event picking for velocity updates. With the “bootstrap” deghosted data as migration input, the imaging gathers show suppression of the ghost energy (Figure 1b).

Demultiple has become another challenge associated with variable-depth streamer acquisition. The ghost response is considerably different from near to far offsets due to the variations...
in receiver depth. By convolving traces with different wavelets, the traditional SRME method produces multiple models substantially different from the input. Sablon et al. (2011) presented an adjusted 3D SRME procedure for variable-depth streamer data. The workflow involves deghosting the input data, and subsequently re-ghosting the “ghost free” multiple model. The modeled multiple better matches the real multiple reflections and gives an improved subtraction result.

In order to improve turnaround time for the fast-track product, a simplified SRME flow was developed for variable-depth streamer acquisition, aided by the improved pre-migration de-ghosting algorithm. Similar to Sablon’s method, deghosting is done prior to the multiple prediction, so that the generated multiple prediction is ghost-free. However, in the simplified flow, the predicted multiple is adaptively subtracted from the ghost-free input instead of re-ghosting and subtract from the data without deghosting. With this flow, the re-ghost step in Sablon’s flow is eliminated, and data after SRME can be treated similarly to conventional data, i.e. it can be used to generate migrated gathers and images for velocity model building and fast-track imaging without further post-migration deghosting. This methodology provides most of the benefit seen in Sablon’s method, and at the same time, significantly reduces the turnaround time for model building and the fast-track imaging.

Figure 1: The left shows migrated gathers and stacks prior to deghosting, the right shows migrated results after. We can clearly see improvements in both the stacks and gathers.

Figure 2: Target line Kirchhoff PSDM showing effects of new variable-depth streamer 3D SRME methodology, with no demultiple (a), conventional 3D SRME method (b), and with new deghosted 3D SRME flow (c). We can see a reduction in residual multiple.

**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 thick complex salt bodies above them. In many areas, a complex top of salt requires scenario testing in order to improve the fast-track model. In addition to the geologic challenge, time constraint is another important factor for the fast-track in the Santos Basin variable-depth streamer survey. Where Sablon’s previous deghosting method required both normal and mirror migrations for each model, Wang and Peng’s pre-migration “bootstrap” approach to deghosting allows us to improve the runtime for each iteration of tomography by only requiring one migration. This creates opportunities to run additional iterations of fast-track tomography within a given time frame, resulting in an improved overall image.

Our strategy is to build an isotropic salt flood model with a coarsely gridded top of salt interpretation. The initial fast-track sediment velocity is derived using velocity trends found in neighboring areas as well as a handful of shallow wells. Several iterations of sediment tomography are performed prior to investigating the top of salt (TOS). The rich bandwidth associated with variable-depth streamer acquisition provides improved details in the sediment tomography, and more accurate salt interpretations. In spite of the time limitation, TOS scenario testing is done in several locations where shallow carbonates are easily mistaken for TOS. One scenario test example is shown in Figure 3. The deeper TOS interpretation (on right) provides a better pre-salt image compared to shallow TOS results (on left). Figure 4 shows the isotropic Kirchhoff fast-track migration of the Santos Basin.

![Figure3: One TOS scenario example. The deeper interpretation provides a more continuous base of salt than picking the shallow reflection. Scenario testing in the fast-track gave an improved pre-salt image and helped develop a better geologic understanding of the region.](image)

![Figure4: These images demonstrate the characteristics of the fast-track results. We can see rich detail in the shallow sections including crisp faulting and layered texture of events, as well as clear pre-salt events enhanced by the improved bandwidth.](image)
Conclusions

In this paper we have shown the need for processing technique adjustments associated with variable-depth streamer data, including low frequency preservation, receiver deghosting, and multiple attenuation. The challenges associated with processing variable-depth streamer data are significant, but the potential for improved imaging make them worth the effort. We have shown, using real data examples from the Santos Basin, the benefits of increased low frequency signal penetration and broader bandwidth associated with variable-depth streamer acquisition. We have seen the benefits associated with variable-depth streamer data: Broadened bandwidth, high resolution, strong low frequency penetration, and the potential for seismic inversion with improved velocity analysis.

A TTI anisotropic migration is planned for production utilizing additional well information that was not available at the time of fast-track velocity model building. While the fast-track stopped at an isotropic salt flood deliverable, the production anisotropic volume will include pre-salt velocity updates as well as intra-salt tomography, providing a more sophisticated velocity field. Testing is ongoing to refine the deghosting and demultiple procedures for the production volume. The production processing is also designed to include higher frequencies, up to 120 Hz, which will add additional resolution and details not seen in the fast-track. The fast turnaround of the fast-track volume allowed for earlier geologic interpretation of the area. With higher resolution input and an anisotropic model, we expect to see improved results in the final migration delivery.

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References


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