Imaging pre-salt targets using OBN data in the Santos Basin – a case study

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Abstract

Ocean bottom node (OBN) data has proven to be of great value in de-risking exploration and production due to its high-quality imaging in the presence of complex geologies (Jouno et al., 2019), such as the Brazilian pre-salt. OBN data provides full azimuthal coverage, long offsets, and good signal-to-noise ratio (S/N) at low frequencies, important ingredients for a good velocity update and illumination. Nonetheless, the OBN imaging and velocity model building (VMB) has its own challenges. We address them in this case study to access the full potential of this data. For VMB, we construct a high-quality velocity model from Time-lag FWI (TLFWI) and tomography. In pre-processing, we remove the strong multiple contamination at pre-salt level with a modified Surface-Related Multiple Elimination (SRME) which incorporates demigrated data. For imaging, we present a novel subsurface angle binning approach which yields significantly better pre-stack angle-gathers. The conjunction of these technologies allows us to obtain excellent post- and pre-stack images with a short turnaround.

Introduction

OBN technology opened a new chapter in geophysical exploration, providing the high-quality images required for studying complex geologies such as the pre-salt plays of the Santos Basin. This information originates from two key elements, reliable velocity estimates and full-azimuth illumination.

Good S/N at lower frequencies, full-azimuth coverage, and long offsets make OBN data the most appropriate dataset for TLFWI (Zhang et al., 2018) to produce a reliable velocity model. The long offsets, up to 23km in this case, allow the recording of deep diving waves, which drive most of the TLFWI updates. The use of low frequencies decreases the risk of cycle skipping due to inaccurate initial models, and the full azimuthal coverage improves the illumination, which is an essential ingredient for FWI as well as imaging below complex salt bodies. Although our current TLFWI could achieve a good V0 model with OBN data, high computational cost and crosstalk impedes us from obtaining other parameters such as those which

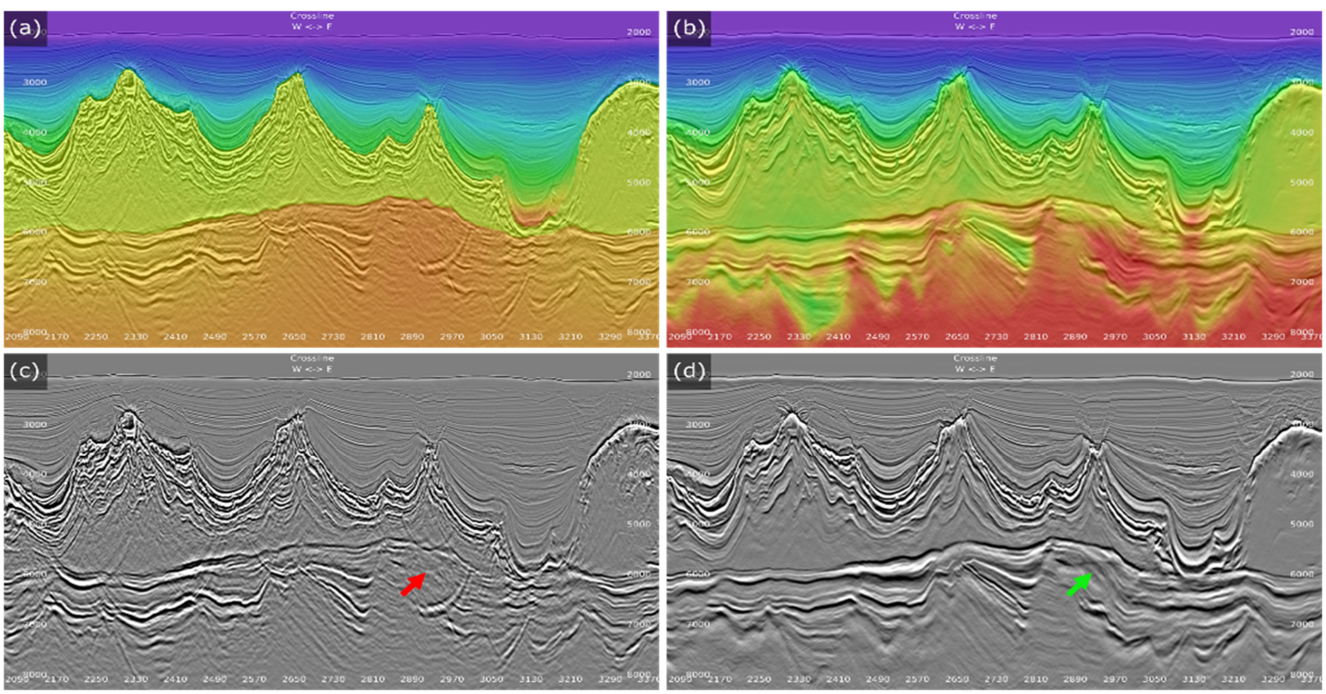

Figure 1. Top: (a) Legacy NATS velocity model and (b) Ultra fasttrack OBN TLFWI velocity. Bottom: (c) RTM image using NATS velocity and NATS data and (d) RTM image using Ultrafast -Track OBN TLFWI velocity and OBN data. Arrows point to locations discussed in the text.

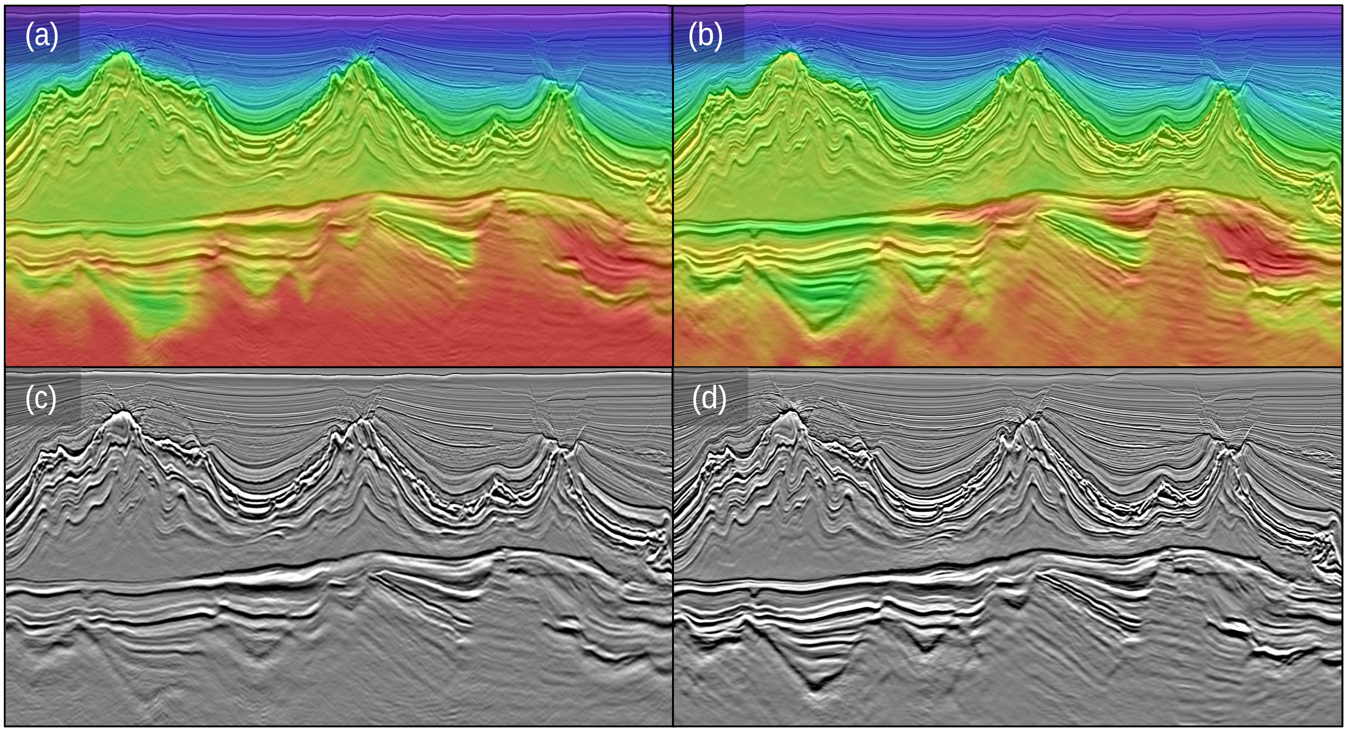

Figure 2. Top: (a) ultra fast track OBN TLFWI velocity and (b) full track iterative velocity. Bottom: (c) RTM image using ultra fast track TLFWI velocity and (d) RTM image using full track iterative velocity.

describe anisotropy reliably. We therefore rely on iterating FWI updates with well-constrained common image gather (CIG) multi-layer tomography (Guillaume et al., 2012) to improve our anisotropy estimate.

Another challenge posed by OBN data is attenuation of strong multiples that interfere with primaries, often at the pre-salt level. To attenuate multiple energy, we use a well-known modelling method, SRME. However, to apply this technology to OBN data, it is necessary to have an auxiliary dataset recorded on the surface. For the Santos Basin, these are usually narrow-azimuth towed streamer data (NATS), which suffer from lack of azimuthal coverage and good-quality low frequencies. Without this information, some multiples are not fully modelled.

In imaging, while full-stack OBN images are generally superior to those from streamer data, the pre-stack gathers may not have the same level of interpretability due to the coarse 500mx500m receiver geometry of the OBN acquisition. The relatively large node spacing leads to poor angle sampling and reduces fold, resulting in noisier gathers. We replace the traditional cylindrical angle binning by a spherical binning approach which improves S/N ratio in pre-stack angle gathers, achieving better balanced amplitude and illumination among different azimuths.

Velocity model building

Due to the poor quality of the legacy NATS image, an ultra fast track processing was carried out with OBN data to create a preliminary image and velocity model in a very short cycle time. The preliminary velocity was obtained using TLFWI only, and this first image was taken as the benchmark to identify where the final products could be improved. Figure 1 shows a comparison between panels (a) and (c), which show the Legacy NATS velocity model and corresponding NATS RTM stack, respectively, and panels (b) and (d), which show the ultra fast track TLFWI velocity model and corresponding OBN RTM stack, respectively. We can clearly see that, with a turnaround of a little over a month, TLFWI with the OBN dataset is able to recover the main velocity trend of the pre-salt packages, which substantially improves the imaging of the features therein, with important uplifts on the pre-salt faults.

Although the image is improved significantly using TLFWI to update the velocity only, to extract the full potential of the OBN data for imaging it is necessary to have a reliable velocity model. We proposed an iterative TLFWI and well-constrained tomography flow to update both velocity and anisotropy parameters for each layer, post-salt, intra-salt and pre-salt. The impact of our velocity and anisotropy update is shown in Figure 2. Figure 2 shows the ultra fast track TLFWI velocities (a) using Legacy anisotropies and (c) its correspondent RTM Stack. The full-track tomography update (b) and its RTM Stack (d) show the benefits of aiding TLFWI velocity updates with well-constrained tomographic updates. The events in the vicinity of the base of salt and the pre-salt layers exhibit improved illumination and coherence. This improvement could not be achieved without the anisotropy updates.

Surface multiple attenuation

SRME requires the data to be recorded at the surface to properly model the multiples. OBN data is recorded at the water bottom, which adds the requirement of an auxiliary dataset to construct the source side field in OBN SRME. In the Santos Basin, NATS data is often available, but given that streamer data lacks good quality low frequency or

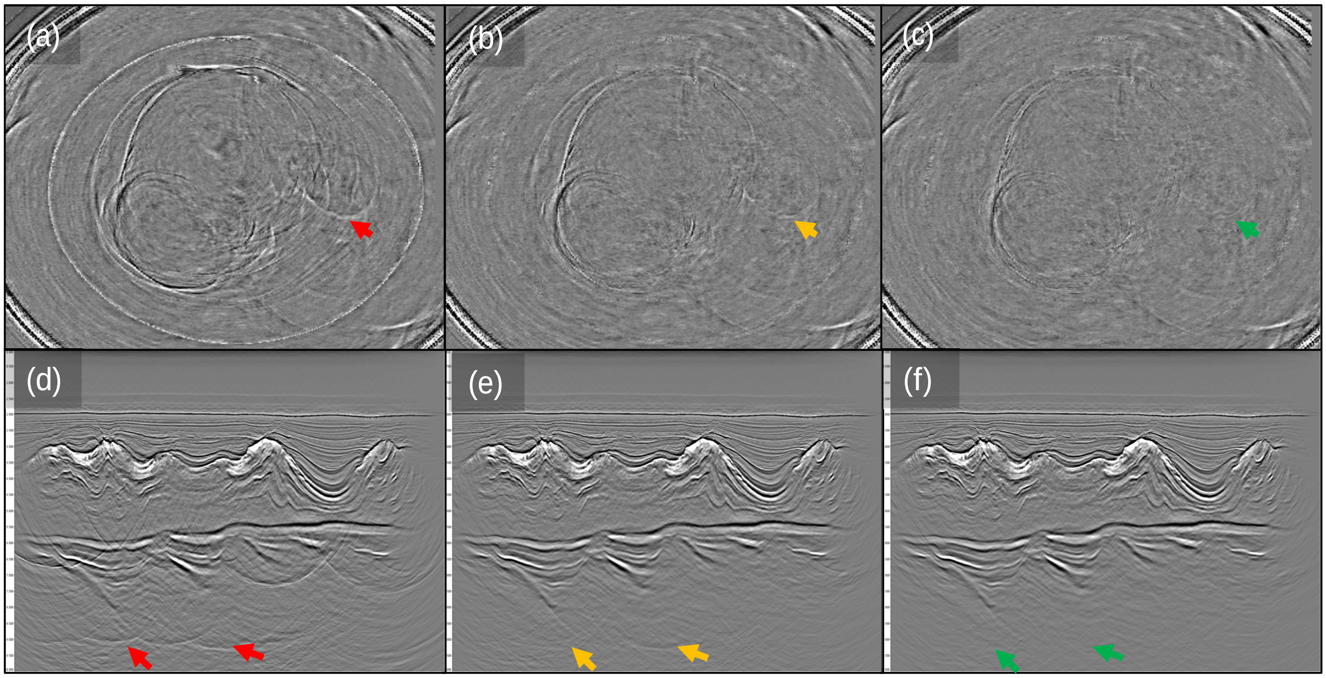

Figure 3. Top: OBN timeslice (a) before SRME, (b) after NATS SRME adaptive subtraction, and (c) after joint NATS + OBN SRME adaptive subtraction. Bottom: OBN RTM image along one inline (d) before SRME, (e) after NATS SRME adaptive subtraction, and (f) after joint NATS + OBN adaptive subtraction. Arrows point to features discussed in the text.

wider azimuthal coverage, using only the NATS data as an auxiliary dataset leads to poor multiple modelling.

To overcome this, we complement the NATS data with full azimuth data demigrated to the surface from the OBN image. We use both auxiliary data to create two multiple models. The first uses NATS data and is capable of modelling most of the mid to high frequency multiples with simpler wavepaths. The second uses the demigrated data and improves over the NATS with lower frequency multiples and more complex ray paths that are common in the presence of salt domes. Since the models are complementary, we combined them in a joint adaptive subtraction flow to reduce multiple contamination.

Figure 3a shows a time slice of a node gather and Figure 3d an inline of the OBN data RTM stack before any multiple attenuation, where the multiples at the pre-salt level can be easily identified. The adaptive subtraction result of the NATS-only multiple model, with the time slice and inline in panels (b) and (e), respectively, still exhibits residual multiple energy (indicated by the orange arrows). This is expected due to the lack of low frequency content in the NATS data. By jointly subtracting both models, much better low frequency content is included in the SRME model, which results in improved multiple attenuation, as the green arrows indicate in panels (c) and (f).

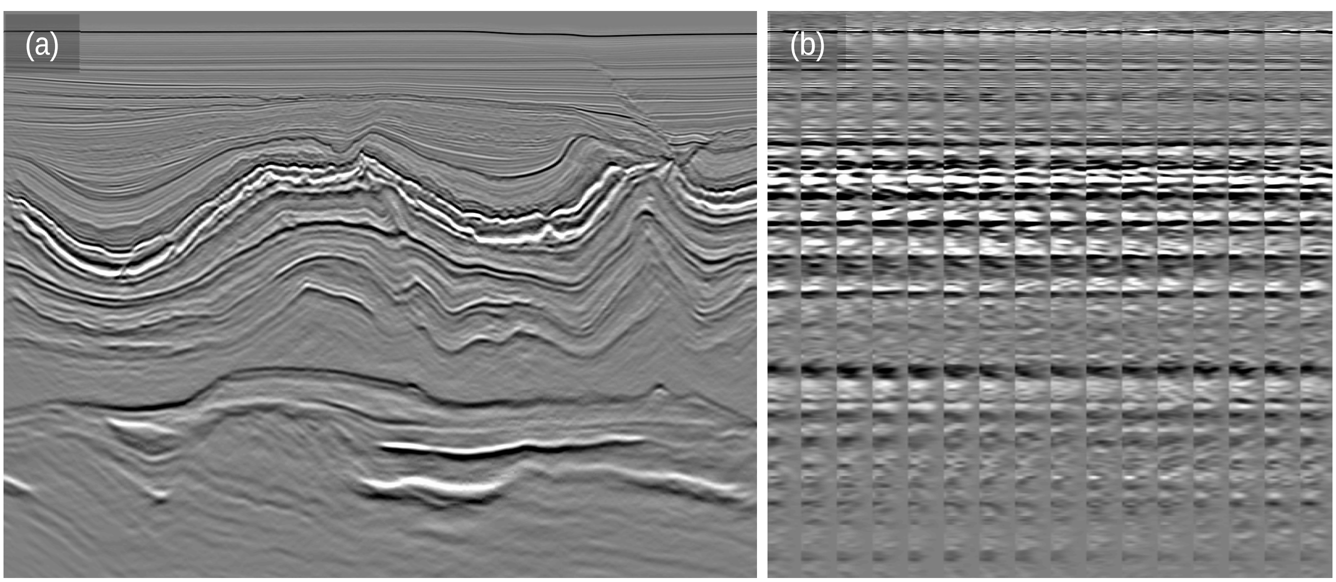

Figure 4. RTM for (a)Angle Stack (b) spherical binning, RTM 3D angle gathers in 16 azimuths and incidence angles from 0º to 50º.

Sampling and illumination in pre-stack domain

OBN full stack data typically have high fold, due to the wide azimuthal coverage. However, to take advantage of AVO/AVA information it is necessary to use a pre-stack migration algorithm. 3D angle-domain common image gathers (ADCIGs) created by RTM are the most suitable for pre-salt imaging because they have the usual advantages of RTM over Kirchhoff algorithms while providing information about subsurface incidence angles. Nonetheless, the quality of partial images is highly degraded due to the poor angular sampling for a given azimuth. Poor sampling stems from the relatively coarse node spacing of typical OBN acquisition geometries. This makes creating a pre-stack image with high S/N from RTM angle gathers (RTM-AG) quite challenging. Historically, pre-stack images are often obtained using surface extensions such as surface-offset gathers (SOG). SOG are generally more robust for measuring gather curvature in simpler geologies, whereas subsurface extensions, such ADCIGs, provide better fidelity in the case of multipathing.

We present a novel approach proposed by Pereira et al. (2021) for the binning of subsurface reflection ADCIGs. We applied this new 3D RTM angle formulation that naturally accounts for the node sampling in a homogenous fashion, improving subsurface reflection estimates through a spherical binning formalism. The proposed scheme is adaptable to different acquisition geometries and is such that all bins have equal areas.

Figure 4 shows (a) RTM-AG stack and (b) RTM angle gathers, separated into 16 azimuths of 20º degrees, each azimuth shows incidence angles ranging from 0º to 50º. The homogeneous spherical binning, where all bins have equal areas, improves continuity on the ADCIGs and facilitates pre-stack analysis like AVO/AVA.

Despite the improvement in the angle sampling, illumination differences in each azimuth due to the complex overburden are still present. To further improve the pre-stack images, the single iteration image domain least-squares (LS) RTM proposed by Wang et al. (2016) has been applied to compensate for variation in illumination among different azimuths and to attenuate remnant acquisition imprint. Figure 5 shows the comparison for the azimuth 0º incidence angle 0º before and after LSRTM (panels (a) and (b)), respectively. The same comparison is shown in panels (c) and (d) for azimuth 0º incidence angle 24º. The improvements from the homogeneous angle sampling and LSRTM are quite substantial in the single azimuth stacks, with much less noise and improved illumination.

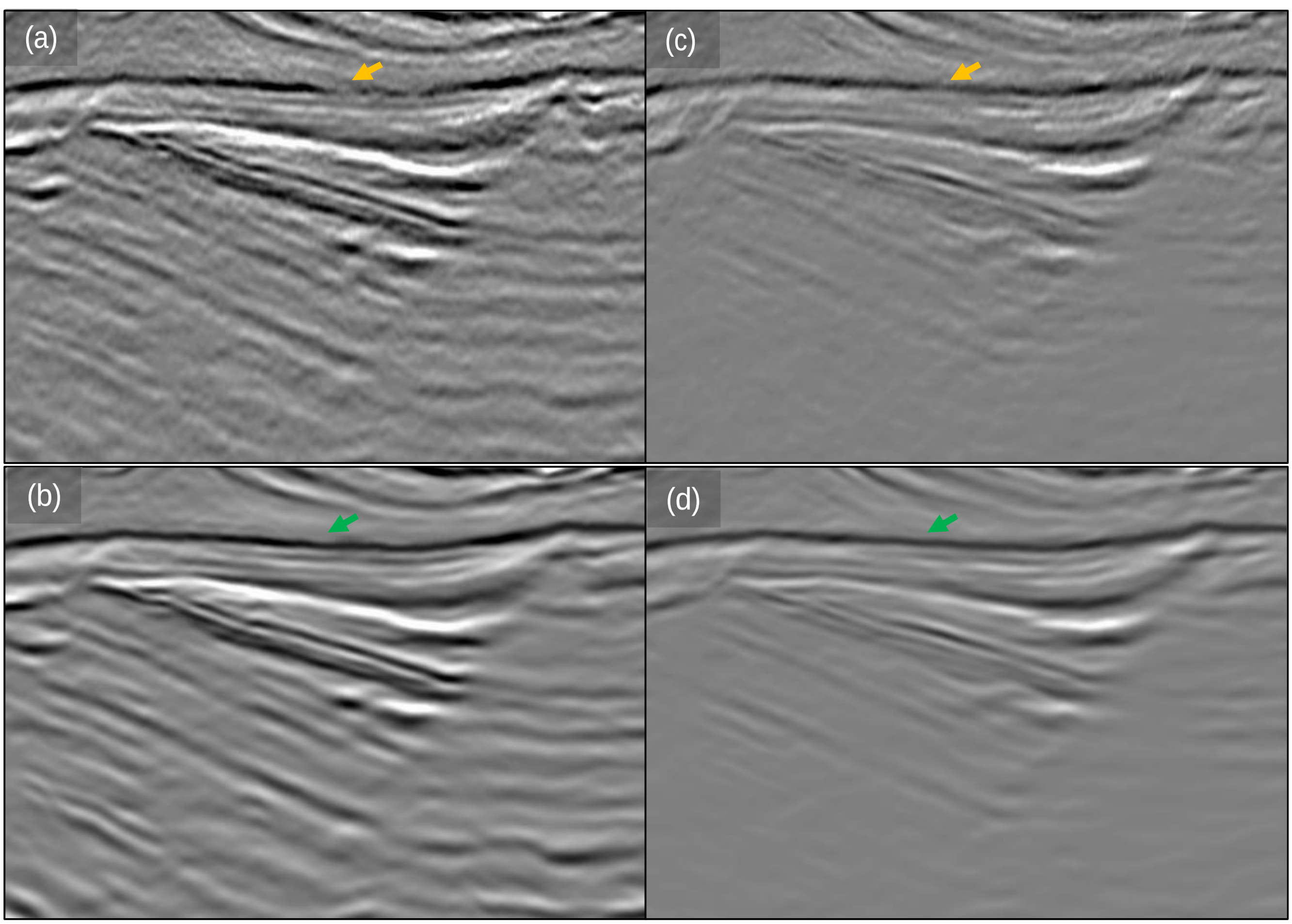

Figure 5. Image of (a) Azimuth 0º Incidence Angle 0º RTM and (b) Azimuth 0º Incidence Angle 0º LS-RTM, (c) Azimuth 0º Incidence Angle 24º RTM and (d) Azimuth 0º Incidence Angle 24º LS-RTM.

Conclusions

With a short turnaround time, we were able to create an image and velocity using OBN data that is already better than a NATS image in the pre-salt. However, to exploit the full potential of the OBN data, new technologies and processing strategies are required. Overall, TLFWI and well-constrained tomography have proven to be suitable for this OBN case study, adding substantial information to the relevant pre-salt structures. The proposed 3D SRME flow using demigrated data improved the multiple model at low frequencies, making the final adaptive subtraction more accurate. Finally, the spherical binning provides pre-stack products with appreciable increase in S/N, and LSRTM was able to compensate the difference in amplitudes due to illumination effects among different azimuths in a satisfactory manner.

It is still necessary to validate the flow in other areas and with different acquisition geometries. It might be possible to implement a more robust flow that may further reduce the turnaround time needed to create the preliminary image. The inclusion of converted waves into our VMB flow could also potentially improve data resolution, and a full 3D designature could enhance the wavelet deconvolution and image resolution.

Acknowledgments

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