The Value of Uplift Processing in Frontier Exploration Basins – Offshore Brazil Case Studies

Introduction

In recent years, the seismic industry has been focusing on optimizing workflows and reducing overall project timelines and costs. With such “lean-and-mean” approach, academia and industry are coming up with a lot of creative solutions with clear benefits but also encounter certain limitations. In this paper, we show how additional time and reprocessing allow for improvements in final imaging that reduce interpretation uncertainties in frontier exploration.

Fast track or early out data products are delivered on aggressive timelines, usually within a few weeks or months upon completion of acquisition. As such, they allow more time for prospect evaluation and decision making. Nowadays, almost all new seismic acquisition programs have fast track components and are usually very effective, if planned and executed well. For example, the regular grid of 2D data allows for more reliable regional velocity model and interpretation framework, that greatly reduces time spent on velocity model building for infill denser 2D or 3D surveys (Cvetkovic et al. 2018). Machine learning algorithms trained on a global data library of noise and signal datasets, can also help handle the impact of swell noise and other common coherent noise trains by the reducing time for testing and application by a number of weeks. Another benefit is early insight into data quality and geological settings of the area that will be later applied to full processing sequences modification.

In frontier basins, the number of geological and geophysical assumptions or uncertainties increases. In return, standard flows from well-established provinces, even with the latest technologies and tools, could lead to subpar results in new projects. Assumptions like the extent or type of salt, diversity and depth of volcanic and velocity-lithology relations along the Brazil passive margin are common when high-grading basin with dense 2D or 3D seismic. We find that partial re-processing or uplift processing with a less aggressive timelines can lead to significant enhancement in imaging, even on recently acquired data. Both case studies we present show that data driven methods such as Dynamic Matching Full Waveform Inversion (DMFWI) along with interpretation support can provide high resolution models that further improve imaging quality.

Outboard Campos Basin

Outboard Campos Basin can be considered a frontier basin as there is still a limited amount of geoscience data coverage. Besides regional 2D lines from 2013 to 2017, there are only 5 wells that resides at the edge of the survey. Regional prospects that are identified on 2D data are extension of NW-SE sag trends described by several authors (Zalan 2020) while outboard of extension is still speculative. In 2019, TGS acquired ~14,100 km² of deep-water 3D Narrow Azimuth (NAZ) survey with 2 phases of acquisition and several early out imaging products with a compressed timeline. This allowed the industry more time to define prospects and propose wells within an exploration time commitment window, set by the Brazil government regulatory. Full pre-processing and model building included the state-of-the-art production workflows, such as DMFWI and Least-Squares Reverse Time Migration.

However, during later stages of processing it was recognized that a single workflow will not work equally well for this large area, especially outside of a central high and an external kitchen (Zalan 2020). One part of the survey had a volcanic complex that is piercing through salt which appeared as a single connected salt body on 2D data (***Figure 1***).

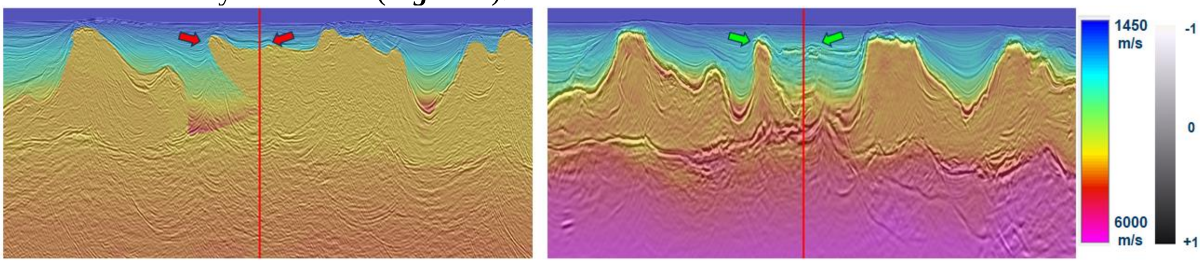

Figure 1 2D vs. 3D imaging of complex salt geometry in Campos Basin. Arrows around red line point to top of shallow volcanics that could not be distinguished from top of salt on 2D data.

Complicated 3D structures cannot be imaged on 2D data even if migrated with true subsurface models, deep and small-scale volcanic intrusions cannot be inferred from potential fields data, hence the need for additional work in this area. Another set of geological features that were not resolved to satisfactory level were salt "snakehead" features compressed between Albian carbonates and other deep mini basin sediments. We found strong correlation between distribution of these features and quality of base of salt imaging as shown in ***Figure 2***. Partial reprocessing of Campos 3D data was done in 2021 and addressed most of these concerns.

First, we revised the initial model by smoothing and clipping sediment background model. We did not change the original salt interpretation as it would require a significant amount of time to manually interpret each salt ridge. Instead, we rely on DMFWI and additional higher frequency bands to derive high details in the model. We also adjusted for supra-salt and pre-salt anisotropy by scanning testing as there are no near-by wells in the area that penetrates the base of salt.

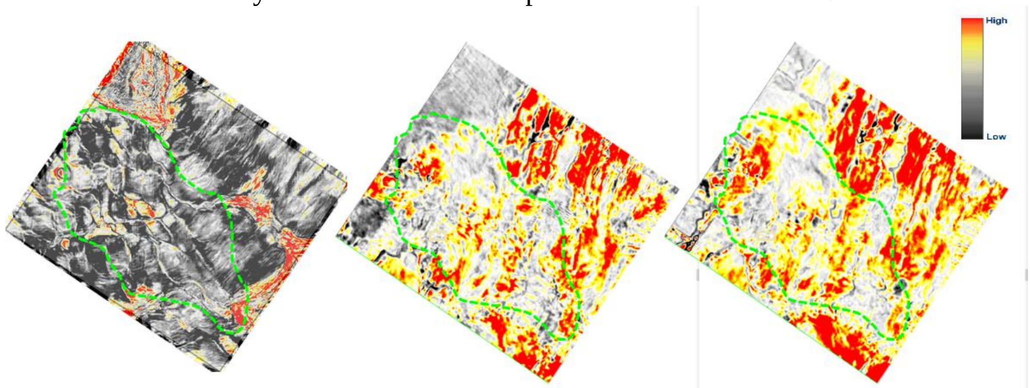

Figure 2 *Amplitude extraction maps: top of salt (left), base of salt from regular processing (middle) and base of salt after uplift processing(right). Green line polygon shows correlation between salt "snakeheads" ridges and poor amplitude along base of salt that was improved after additional work.*

We see limitations on 3D NAZ data with only 10km of offsets, and along with DMFWI acoustic solution, we found the need to edit certain parts of the model, especially around salt – sediment interfaces. As for pre-salt and deep section updates, since DMFWI utilized reflection part of the wavefield, we obtained nicely delineated velocity features when the top of the salt geometry is not overly complicated. These are interpreted as carbonate platforms and build-ups which present primary economical reservoirs like recent inboard discoveries (Tupi).

As for volcanic intrusions through the salt, we preserved much of the updates from DMFWI with minimal edits. Manual interpretation of these features is possible but delineating high resolution velocities where thin and tilted basalts interleaving with sediments would be extremely challenging. We managed to derive a great number of velocity details from DMFWI and provide uplift to the image beneath these features. It is crucial for seal analysis as salt welds in this area are relatively thin and could be broken by normal faulting or volcanic intrusions.

Figure 3 shows a typical section from the partial reprocessing of the Campos 3D dataset. Overall, we see improvement in imaging at every depth with the base of salt and pre-salt section showing more connected and more coherent events. Pre-salt reservoirs are also better imaged and their extent refined based on this newly imaged data. Area and volumetric analysis along key regional horizons, such as RMS amplitude extraction as well as residual moveout further support such observation. ***Figure 2*** shows better resolved velocities in area with salt "snakehead" features greatly improve imaging along the base of salt. Despite noticeable improvements we acknowledged the limitations of working in Campos basin with 3D NAZ data as suggested by Zhuo et al. (2022). Advanced synthetic models such as SEAM for Campos Basin could help us better understand remaining imaging challenges in this area such as pre-salt normal faults relation to thinning oceanic crust, CO_2 content in reservoirs, external kitchen migration pathways and volcanics at the base of salt.

Potiguar Basin, Offshore Brazil

Offshore extension of Potiguar Basin is still very much a frontier basin as there has only been 3 wells drilled. Pitu well (1-RNS-158), drilled in 2013 is the only one with a hydrocarbon discovery.

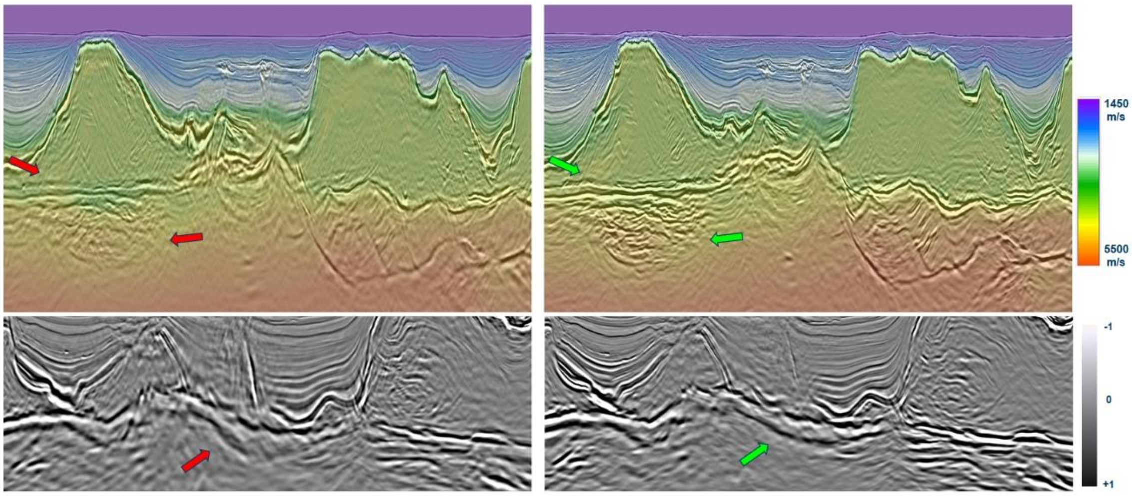

Figure 3 *Imaging improvement in the most geologically complicated part of the survey after limited reprocessing. Notice better stacking response and cleaner image at base of salt and pre-salt sediments.*

Insights into prospectivity, as in other basins, have been directly linked to data availability. Isolated 2D lines acquired in 1990's and early 2000's, then several phases of 2D lines shot on regular grid and the large 3D NAZ seismic data (~10,600km²) covering most of the basin was acquired in 2018. Although underlaying 2D grid was processed utilizing modern pre-processing and imaging workflow, there were still a lot of unknowns about this basin until 3D dataset became available. 2D seismic will have limitations in a lot of basins. In this case we had sparsely separated 2D lines (10-20km), very rugose water bottom and deep canyons and complex subsurface geological setting. A 3D survey was designed and executed with a very aggressive processing timeline and multiple fast tracks, which allowed for early look interpretation. While primary objectives of these products were met, additional time spent on each of the fast track subsets (5 versions total) compromised time spent on final products. Applying all the latest algorithms, such as RTM, has a time and cost implication to the project which in this case provided minimal uplift in final image as the models were built with conventional modeling workflow - tomography and Kirchhoff PSDM.

Different legacies of 2D data along with gravity and magnetic interpretation have indicated a volcanics in this area where Fernando flows from north meeting with Macau flow from onshore south across most of this 3D data coverage. To accommodate model building of these variable thickness and rugosity volcanics, original time assigned for manual interpretation had to be increased based on fast track results. The best results in original processing were obtained with a combination of several passes of manual interpretation and tomography, although there were clearly several places where pre-volcanic structures could be better imaged (***Figure 4***).

We first tested DMFWI on a subset that covers more complicated geology with the most difficult part of the subsurface to image. We ended up with a starting model that was a very smooth version of the final model eliminating detailed volcanic geobodies interpretation. After minor adjustments to water bottom interpretation, we ran 4 frequency bands of DMFWI up to 12Hz over the entire 3D. We QC each band in the data and image domain and ran additional model edits and post DMFWI tomography to get to the final model. We also ran more quantitative areal and volumetric QCs such as gather flatness volumes and extraction along horizons, where the reprocessing gathers are consistently flatter than legacy from the water bottom to the target level (***Figure 5***).

Although this work had almost no interpretation of surfaces and manual picking, we still did detailed evaluation of models and validation images to minimize artifacts due to workflow and data limitations. One of the main challenges was removing small scale artifacts due to acquisition imprints and uneven illumination whilst retaining relevant geological features associated with volcanics, such as subvertical and vertical volcanic calderas. The benefits of a data driven workflow are shown in ***Figure 4***. Although a very detailed top of volcanic interpretation can be done, velocity variation within these geobodies, such as sediment flows, or tilted basalt blocks will be challenging relying on manual intervention. A high-resolution model derived from DMFWI provides solution that "heals" structures underneath volcanics, simplify structures and provide overall better stack response.

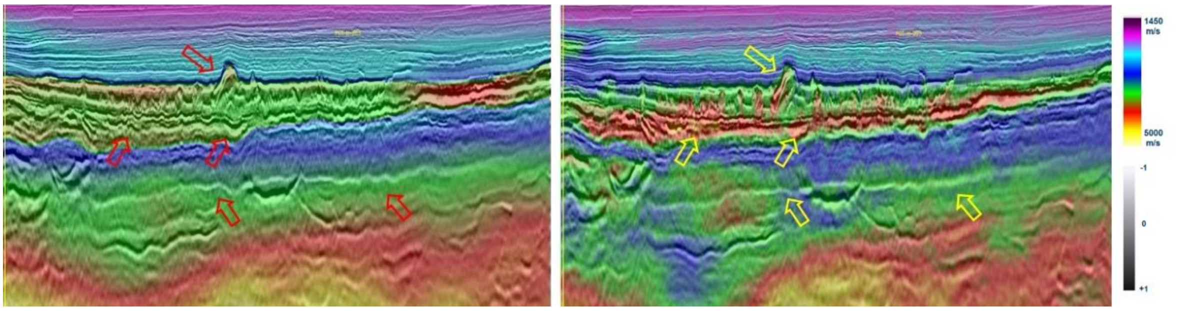

***Figure 4** Undulation and artificial structures in original processing despite detailed volcanics interpretation and intra-volcanic tomography model (left). DMFWI alleviate undulation at base and beneath volcanic geobodies (right).*

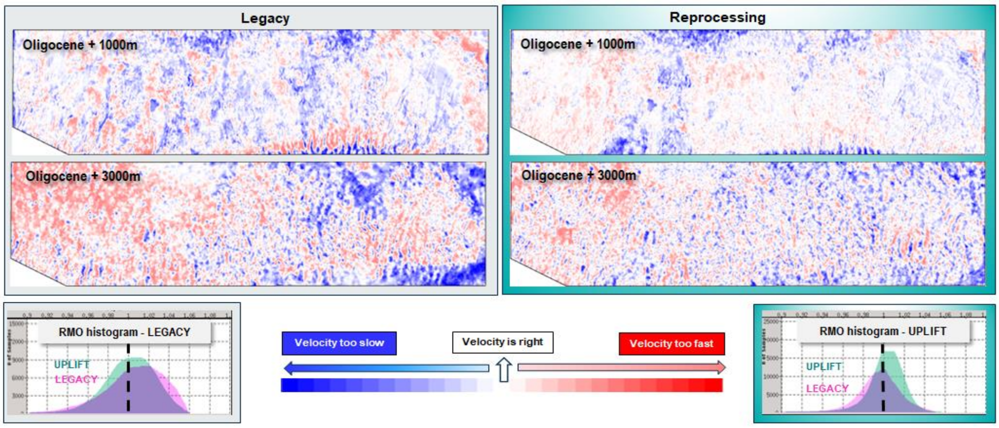

***Figure 5** Quantitative QC showing gather flatness at different depth levels in the survey. Oligocene horizon was chosen as it was the age of major volcanic activity in this area.*

Conclusions

We have shown two case studies where partial reprocessing led to an uplift in imaging and model building while reducing uncertainties in risky frontier exploration. In outboard Campos Basin, simplifying the starting model and fine-tuning parameters of DMFWI along with altered post-processing flows produces a much better image in this complicated geological setting where volcanics pierced though salt bodies. Although data driven workflow like DMFWI are very robust, we see the need for geologically oriented QC of results to minimize artifacts caused by data limitations.

For Potiguar basin, we demonstrated that DMFWI model provides significant imaging improvement. The volcanic bodies are extremely complex and vary over vast project area that two passes of manual interpretation will still underperform compared to a simplified starting model and DMFWI workflow. High resolution details such as delineated volcanic calderas can be obtained despite 3D NAZ data with offsets limitation incorporating careful QCs and tailored postprocessing. Although machine learning and fast track workflows can reduce overall timelines, we found that the best project outcomes are the ones where agile integrated teams work from planning to completion of the project, with continuous involvement of all team members.

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