Resolving geological complexity with legacy streamer survey: Potiguar 3D offshore Brazil case study

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Summary

Many of the successful Full Waveform Inversion (FWI) examples involve long offsets and low frequencies along with full azimuth geometries as they are key elements in deriving optimal FWI results (Roende et al, 2020; Huang et al, 2020; Mifflin et al, 2021). The Narrow Azimuth (NAZ) limitation is particularly significant in FWI when dealing with complex subsurface structures as it can compromise the ability to accurately capture small-scale features and velocity anomalies. In a conventional model building approach that relies on image domain ray-based algorithms, 3D interpretation with the aim of delineating geological features may be required to overcome the linear assumption limitation. In this paper we showcase that despite many of the limitations in a Narrow Azimuth (NAZ) setting, Dynamic Matching Full Waveform Inversion (DM FWI) (Mao et al, 2020) is feasible in delineating small-scale volcaniclastic features and structural complexity, overcoming many of the challenges encountered with a tomographic and manual interpretation driven workflow.

Geological Settings

The Potiguar Basin is considered a frontier basin due to the limited drilling activity, with only three wells drilled to date. Among them, the Pitu well (1-RNS-158) drilled in 2013 is the only one that resulted in a hydrocarbon discovery. The rifting in the Potiguar Basin occurred in two phases: Barremian-Aptian offshore rift phase and Berriasian-Barremian onshore rift phase, which elongated the continental Potiguar basin. The main play types are Aptian and Upper Cretaceous turbidites, as well as younger fluvio-deltaic sandstones. Potential source rocks are early to late Aptian shales deposited in a lacustrine-brackish to saline anoxic environment, along with Albian to Turonian marine black shales (Etherington et al, 2021).

One of the many imaging challenges are the shallow Eocene-Oligocene volcanics, which cover more than a third of the survey and are more prevalent in the western portion of the basin. These volcanoclastic features pose model building and seismic imaging challenges and may hinder identification of potential oil and gas lead. There are two distinct volcanic events known as the "Macau" and "Fernando" flows.

The Macau flows represent continental volcanism, resulting in lobe like deposits from distributary channels on-shore and near-shore. The lithology of the subaerial compounded braided lava flows varies with variable thickness and average velocities ranging from 3,500-5,000m/s, based on onshore well data. Fernando Flows are associated with hot-spot volcanism that created Potiguar seamounts, the Fernando de Noronha Archipelago. These volcanic bodies are larger and have not been sampled by any wells. They progressively thin towards the depocenter of the basin and partially overlap with the outer braids of the Macau flow.

Survey Introduction

Located at the eastern end of the Brazilian Equatorial Margin, the Potiguar 3D survey covers ~10,500 sqkm acquired in 2019. Due to economical and practicability drivers, the survey was recorded in a NAZ setting with 8km maximum offsets with cable spacing of 100m, shot in 25m flip-flop fashion. The survey was originally processed with an aggressive timeline due to a licensing round. This legacy velocity model workflow was comprised of iterative passes of tomography including manual interpretation of the volcanic geobodies (Bartlett et al, 2020). The manual interpretation was deemed time and labor intensive due to complexity of the volcanic bodies as these features manifest in varying thicknesses and shapes. Furthermore, an inferior image due to a suboptimal velocity model can hinder judgement of human interpretation and it is almost impossible to capture every fine detail of these rugose top and base volcanic geobodies, as very often we rely on sparse grid interpretation due to project timeline constraint and practicality.

DM FWI Model Building

Water depth over the Potiguar 3D survey varies from ~ 600m to 3800m but most of the area lies in water depth of 2000m or more. With maximum offsets of 8km, the survey suffers from a lack of diving waves which is the robust part of any FWI algorithm (**Figure 1**).

We recognized the pitfalls of NAZ streamer data as this type of geometry is lacking in illumination and azimuthal angles constraint perpendicular to the acquisition direction, leading to sub-optimal FWI applications. In addition, most towed streamer NAZ surveys are lacking in low frequencies which are the key elements to avoid cycle-skipping or to provide meaningful kinematic changes with most FWI application. FWI carries significant advantages over a conventional ray - based method. Not only is it capable of delineating high resolution that are more conformable to geology (Huang et al, 2023), but it also provides the advantages of reducing the lengthy effort in prepping field data for conventional model building. Despite the limitations posed by the survey conditions, we were confident that FWI could be customized to effectively capture small-scale features associated with volcanoclastic deposits. We conducted a pilot study of ~ 400 sqkm over the eastern area which covers the larger tabular volcanic geobodies. These geobodies are characterized by chaotic seismic pattern with few continuous reflectors indicating interbedded magma flows with sedimentary material (Fonseca, 2020), which poses challenges for conventional tomography or human interpretation.

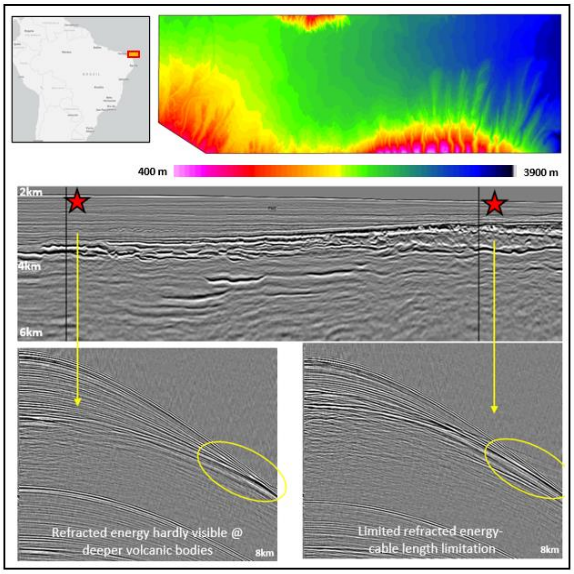

Figure 1: (Top) Location of Potiguar 3D survey & water depth. (Bottom) Examples of shot gathers in ~ 2200m water depth to show case limited diving waves

DM FWI utilizes multi-channel local cross-correlation to assess waveform similarity and phase differences. By employing a multidimensional window approach, it leverages the lateral coherence of the signal and noise, enhancing the robustness of the matching process. It considers all wave modes and prioritizes kinematic differences over amplitude effects. The entire wavefield, including refraction and reflection with limited signal processing was input into the inversion study. For the DM FWI starting model, we relied on the legacy model but reverted to the relatively simple fast-track legacy model which encompassed only two passes of tomography without explicit modeling of the volcanic features. The final legacy model was a less than ideal DM FWI starting model as uncertainties in explicit volcanic geobodies delineation could hinder convergence of DM FWI. We expect DM FWI to perturb the velocity in the order of +/-800m/s, thus eliminating the requirement to seed the volcanic intrusions as the reference velocity.

DM FWI was conducted in a multi-scale manner comprising four frequency bands starting from 4 Hz up to a maximum frequency of 14 Hz. Data and image domain QCs were incorporated during the inter-band DM FWI for assurance of gradual improvement. Results on the pilot showed good uplift and we later extended the DM FWI VMB workflow to cover the entire survey.

Observations and Challenges

DM FWI derived exceptionally good results for most of the survey where the water depth is relatively shallow, especially where we have limited presence of diving waves information in an area where some of the volcanic features resides at shallower depth. Despite starting from an over-simplified velocity model, we see DM FWI delineated geology conformable volcanic geobodies automatically, captured highly irregular interbedded igneous inclusions, effective in alleviating underlying structural undulations and better revealed the exploration targets (**Figure 2 & 3**). These undulations are prevalent either with the fast-track model or the final legacy model. Additionally, DM FWI also delineated very thin sills and dikes, beyond the resolution that can be resolved by tomography or manual interpretation (**Figure 4**).

We faced higher challenges towards the outboard ultra-deep water (~ > 3000m). Along a very rugose canyon in the southern section of the survey, we observed some localized cycle-skipping artifacts. Nevertheless, we successfully captured small volcanic debris sheets in the shallow section (**Figure 5**) using DM FWI and utilized tomography to address cycle skipping issues. Post DM FWI, a pass of shallow tomography was applied to resolve some remaining residual moveout which further improved gathers flatness. An additional pass of deep tomography was also applied targeting the deeper section as FWI depth penetration updates are limited due to this short offset survey. With the tomography updates at depth complementing DM FWI in the overburden, we see notable improvements in the underlying tilted fault blocks imaging.

DM FWI Model Conditioning Lesson Learned

After FWI updates, model conditioning is commonly used to remove artifacts caused by acquisition or illumination issues. The challenges we saw were that even applying a very conservative smoothing can reverse the positive uplift of DM FWI achieved in the region characterized by volcanic geobodies. Smoothing alters velocity magnitude and distorts small-scale volcanic intrusions, reintroducing structural undulations (**Figure 6**). After several trials of alternative model treatment, our solution was to preserve the DM FWI updates in these localized areas by relying on geological masks.

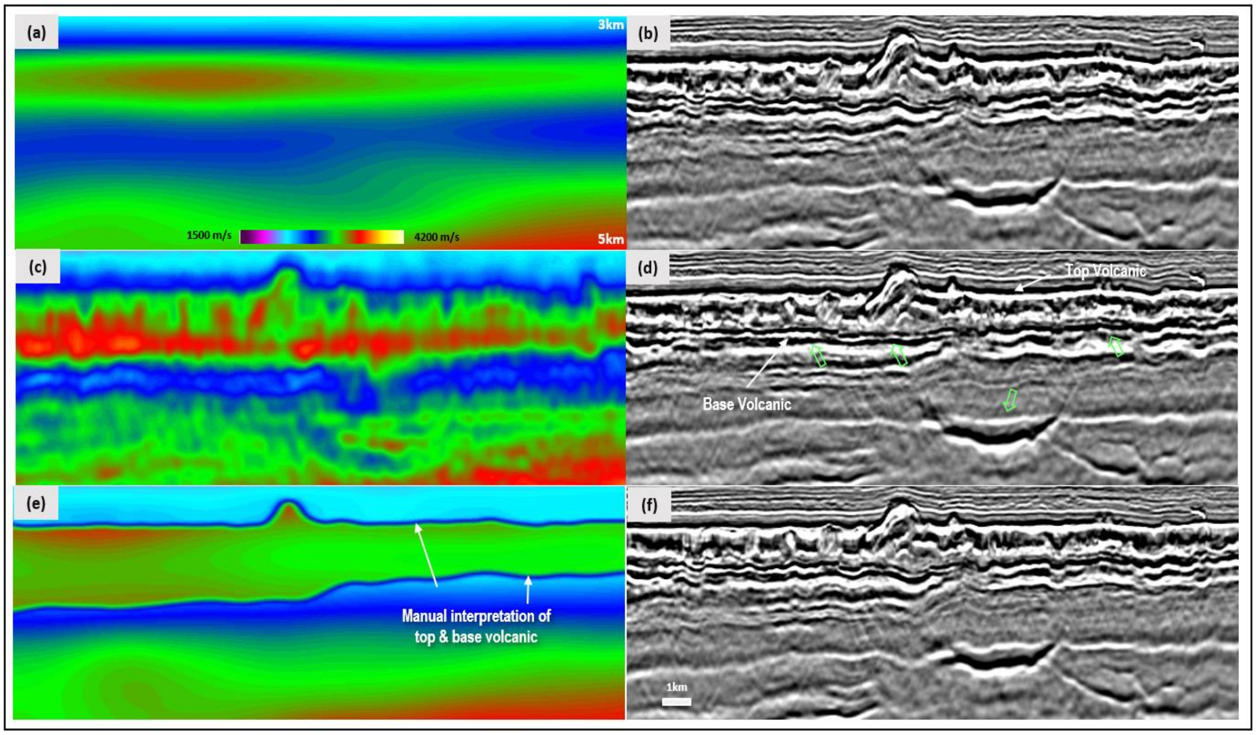

Figure 2 (a) & (b): DM FWI starting model without explicit top/base volcanic body interpretation & the corresponding image. (c) & (d) velocity model and Kirchhoff image after DM FWI. Notice the top/base volcanic body and details within the geobody delineated. Undulations at the base volcanic and the beneath structure are mostly alleviated compared to the starting model or the legacy image. (e) & (f) shows the legacy velocity model & corresponding image.

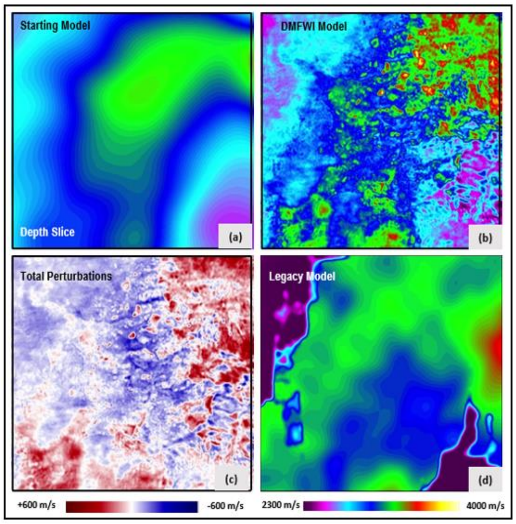

Figure 3: An example depth section that slice through volcanic geobodies in the survey (a) DM FWI starting model (b) & (c) DM FWI update model & total dV (d) Legacy Model

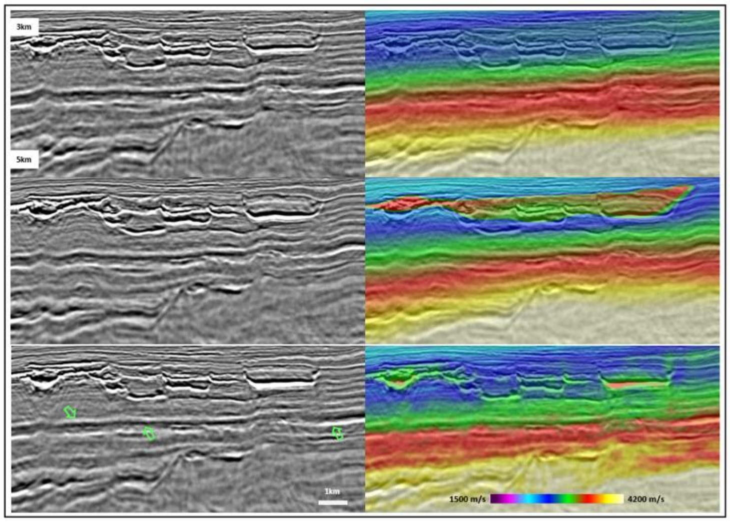

Figure 4: (Top) DM FWI initial image/model. (Middle) Legacy image/model with explicit volcanic interpretation. (Bottom) DM FWI automatically capture thin sills and alleviated undulations underneath these features

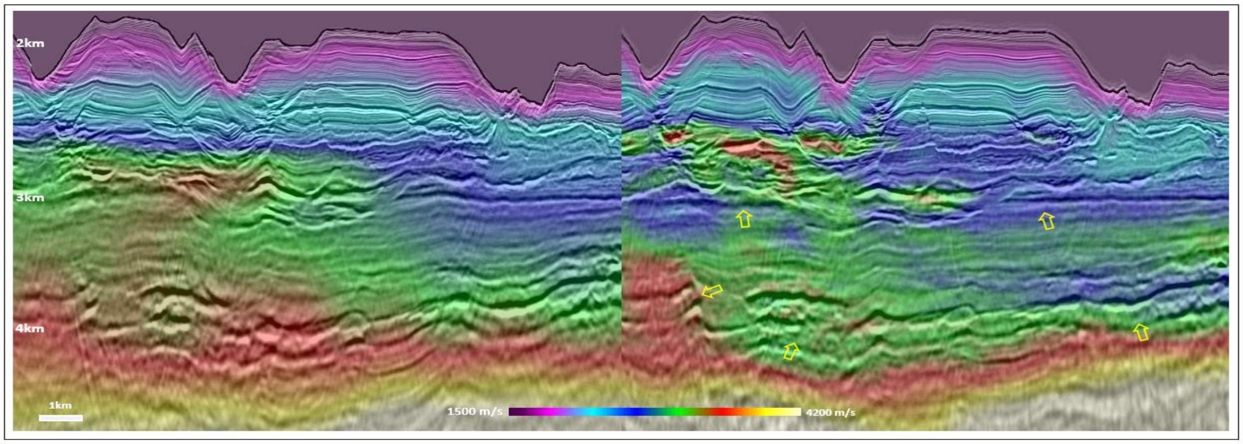

Figure 5: (Left) Legacy image/model. (Right) DM FWI captured the small sheets of volcanic debris in the shallow, alleviating undulation beneath canyon and tomography further improved deeper structural continuity

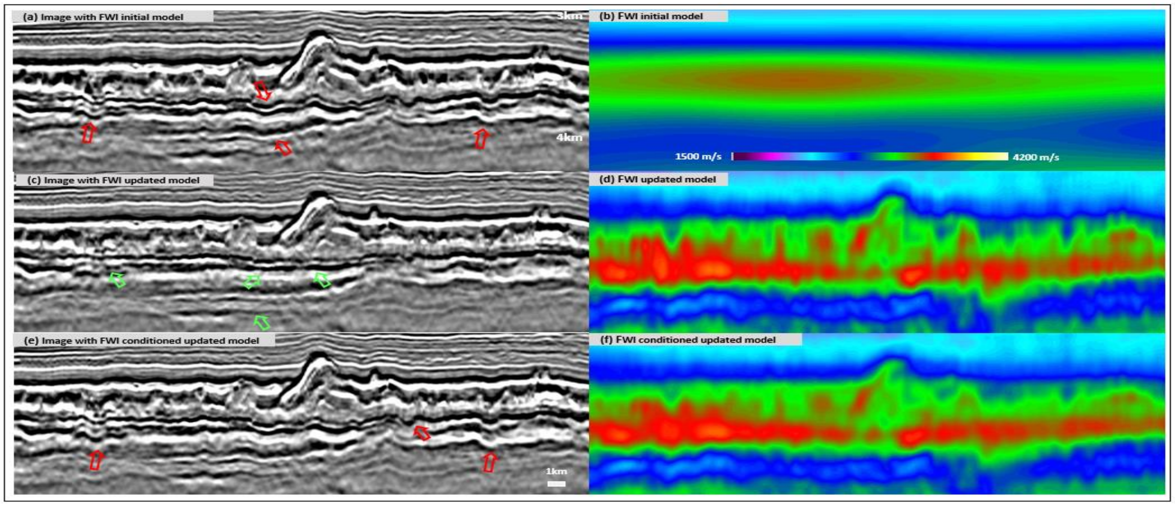

Figure 6: (a) & (c) Image and DM FWI initial model which has minimal details. The base volcanic and reflectors beneath the volcanic body are undulated as the over-simplified model does not represent the small-scale igneous rock intrusion variation required to correct for the model errors. (c) & (d) are the respective DM FWI updated image & model where the undulation at the base volcanic and the image below are being alleviated. DM FWI model smoothing with the intention to remove model artifacts and acquisition imprints unfortunately removed some of the small-scale intrusion details as well as altered the velocity magnitude resulting undulation being introduced back in the image, as seen in (e) & (f)

Conclusions

Despite the limitations of the NAZ survey, we showcased the numerous advantages of a data domain FWI approach in addressing geological complexity. Starting from a simplified model, we successfully derived a more accurate model that effectively explained the field data. This model automatically identified and delineated conformable volcanic geobodies, capturing crucial small-scale intrusions that unlock additional hydrocarbon potential and enhance prospect recovery. Our approach significantly reduced model building time by eliminating laborious manual interpretation typically required for tomography updates, which proved less effective in this geological context. In this case study, we highlighted the importance of careful quality control, as improper model conditioning can reverse the positive results achieved through FWI.

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