Resolving geological complexity with legacy streamer survey, part 2: Application of DM FWI to sub-optimally acquired data

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Summary

Dynamic Matching Full Waveform Inversion (DM FWI) has been established as a proven toolkit to update velocity models. Mao et al. (2020) demonstrated its success for datasets where long offsets, wide azimuths are available. Yong et al. (2023) showcased reliable and effective updates for offsets ranging from 8 km to 10 km utilizing modern 3D Narrow Azimuth (NAZ) datasets in complex geological settings such as salt basins (Santos and Campos) and volcanic margins (Potiguar basin). Here we are extending the application of DM FWI to shorter cable lengths (6km and 7km) for 3D and 2D NAZ streamer data, focusing on Atlantic passive margin settings. Since DM FWI uses both the refraction and reflection parts of the wavefield, we are able to update high-resolution and geologically plausible models covering exploration target depths, from the water bottom to source rock. However, due to the limitations in sub-optimal azimuth coverage and relatively short offsets, model building is supplemented with additional information and model conditioning.

Introduction

The ideal conditions for successful application of Full Waveform Inversion (FWI) necessitate high SNR for ultra-low to low frequencies, long to super-long offsets, and complete azimuth coverage. However, practical constraints such as financial and operational limitations, often hinder the acquisition of such optimal datasets. Yong et al. (2023) have demonstrated that even with datasets that fall short of these ideal conditions, the application of the method known as Dynamic Matching Full Waveform Inversion (DM FWI) can still yield optimal results.

In our current study, we expand the application scope of DM FWI algorithm by employing two distinct datasets characterized by sub-optimal acquisition parameters. The first dataset originates from offshore Namibia in the Orange Basin, comprising eight vintages of 2D surveys acquired between 1989 and 2017 (Figure 1). The varying minimum usable frequencies and maximum offsets across surveys pose additional challenges in resolving small geologic features. Maximum offsets span from 3.6 km on older surveys conducted in shallow water environments to 10 km on more recent surveys.

The second dataset consists of a 3D NAZ survey located offshore Uruguay, comprising of four datasets with different acquisition azimuths and maximum offsets (6 and 7 km). These datasets were seamlessly merged into a single volume with a total size of 25,000 km².

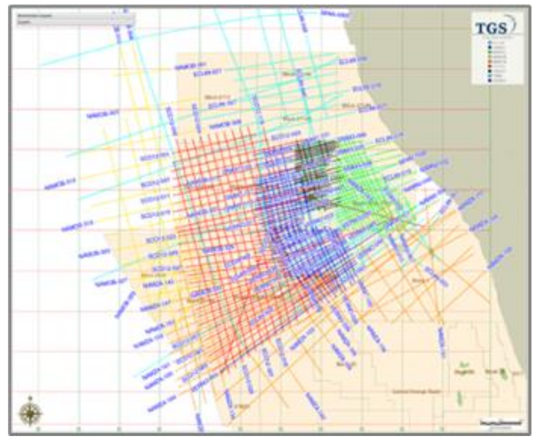

Figure 1: Map showing location of 2D lines in the Orange Basin offshore Namibia.

Case study 1 - Orange Basin Namibia

The Orange Basin, situated along the South-Western African coast, reflects various tectonic occurrences. Notably, the rifting of continents, a pivotal element in the basin's tectonic history, played a significant role. The separation of South America and Africa during the Gondwana breakup was instrumental in shaping the region. As these continents drifted apart, rift basins emerged, and sedimentary processes gradually filled these depressions. Subsequent tectonic events, such as the opening of the South Atlantic Ocean, continued to influence the Orange Basin. The basin's tectonic evolution involves intricate interactions between the African and South American plates, resulting in subsidence, uplift, faulting, and the development of structural features (Vera et al. 2010).

Given the offset variations in different surveys, we conducted an experiment to assess the model update sensitivity in response to the maximum offset present in the data. Using a 2D line with complex geological structure, we investigated how a detailed velocity model could be derived while varying the maximum offsets of the data, with all other parameters held constant. Figure 2 illustrates the results, showing velocity perturbations overlaid on the stack. We employed three different offsets (6, 8, and 10 km) and ran three bands of DM FWI, starting with the lowest available frequency and progressing up to 12 Hz. It is evident that a smaller maximum offset led to a shallower and lower magnitude update compared to results with the larger maximum offset.

The experiment helped establish expectations regarding the satisfactory results for each survey, while also highlighting challenges in deriving a consistent velocity model that accurately reflects the underlying geology and simplifies the geological structure.

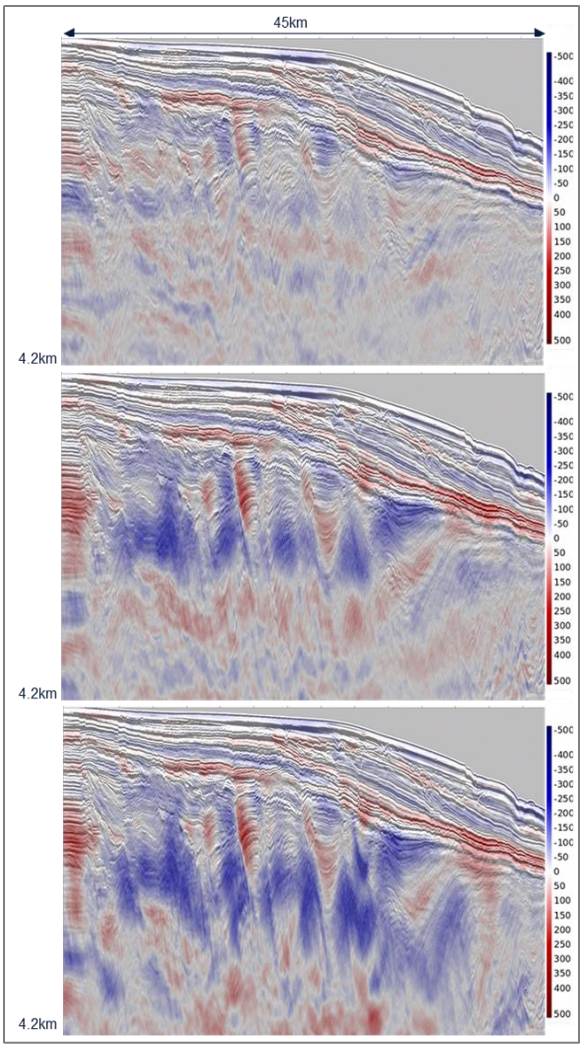

Figure 2: DM FWI velocity perturbations overlaid on stacks, derived from 6 km maximum offset (top), 8 km maximum offset (middle), and 10 km maximum offset (bottom).

The primary objective of DM FWI was to delineate small geologic features, such as channels, faults, and folds in the near surface, leading to a simplified representation of the underlying structure. The velocity model workflow incorporated three tomography iterations preceding DM FWI. Anisotropy was derived and validated at well locations, and the anisotropy fields were created by propagating an average function between the water bottom and a Hauterivian break-up unconformity (shallow water) or basement (deep water) horizon. Subsequent to DM FWI updates, edits and additional long-wavelength tomography were performed. In certain instances, edits were deemed necessary, likely attributed to limitations in 2D data such as feathering and out-of-plane issues.

One of the standard quality controls post DM FWI involves examining the synthetic and observed data matching on a subset of shot locations. Figure 3 shows a comparison between synthetic and observed shots (interleaved) before and after DM FWI, the comparison revealing a significantly improved match of events following the velocity update.

To highlight the value of DM FWI on 2D data, a specific example of a near-surface channel causing a disruption in the underlying geology was chosen. The Kirchhoff Pre-Stack Depth Migration (PSDM) stack section in Figure 4 illustrates an enhancement in stacking response (circled area) beneath the shallow channel feature (indicated by the green arrow). Tomography alone struggles to accurately delineate lateral velocity changes associated with this channel, whereas DM FWI excels in precisely capturing such variations. The outcome is a simplified structural image beneath the channel.

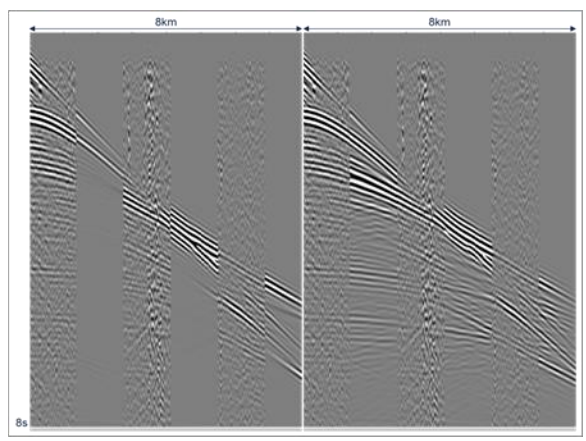

Figure 3: Comparison of synthetic and observed shot data sets before (left) and after DM FWI (right).

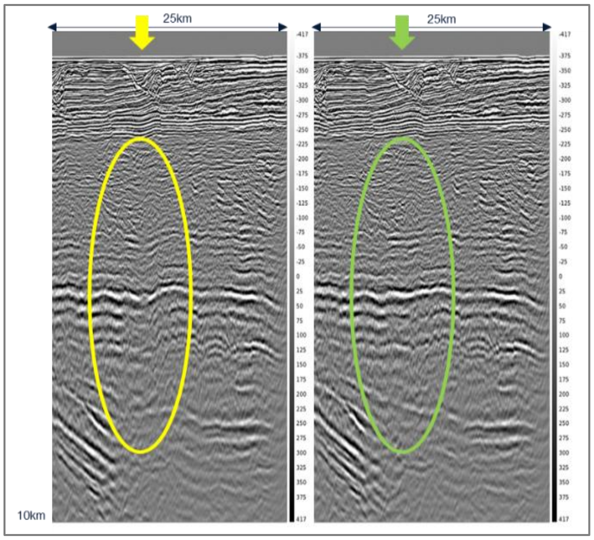

Figure 4: Kirchhoff PSDM stack before (left) and after (right) DM FWI update. Circled area shows an improvement in the stacking response due to better shallow channel delineation (green arrow).

Case study 2 - Offshore Uruguay, 3D NAZ case study

The second case study comes from offshore Uruguay from a re-processing of four individual legacy surveys to create a merged volume. These extensive 3D datasets enable geoscientists to work on the uncharted South Atlantic margin and develop new play concept systems at both regional and local scales. Reuber et al. (2023) described pre-processing workflows including tomography model building, while discussing regional prospectivity based on this new dataset. Here, we focus solely on the DM FWI component of the velocity model building workflow.

Figure 5 shows a map of legacy surveys with the examples we are showing positioned between surveys A and B. We selected this subset as the "worst case" scenario due to the relatively shorter maximum offsets of 6 km and 7 km, respectively. This area is characterized by strong seasonal currents and complex bathymetry; hence the data quality is lower compared to the rest of the survey area.

We apply DM FWI workflow in four bands, working from lowest usable frequency up to 15 Hz. The starting velocity model for FWI is from a regionally constrained tomography model (interpretation and Raya-1 well - only well in the survey). Following the final band of DM FWI updates, we apply post DM FWI long wavelength tomography with additional model conditioning.

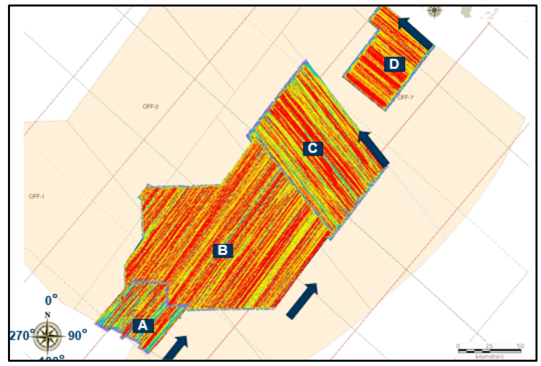

Figure 5: Map showing layout and acquisition direction of different legacy surveys used for the Uruguay survey. Survey A was acquired with 6 km cable, survey B with 7 km and surveys C and D with 8 km cable.

Figure 6 shows Kirchhoff PSDM stacks and respective velocity model overlays before and after DM FWI. Arrows highlight areas where updates predominantly enhance imaging quality originating from shallower fine-scale adjustments around the regional Oligocene unconformity.

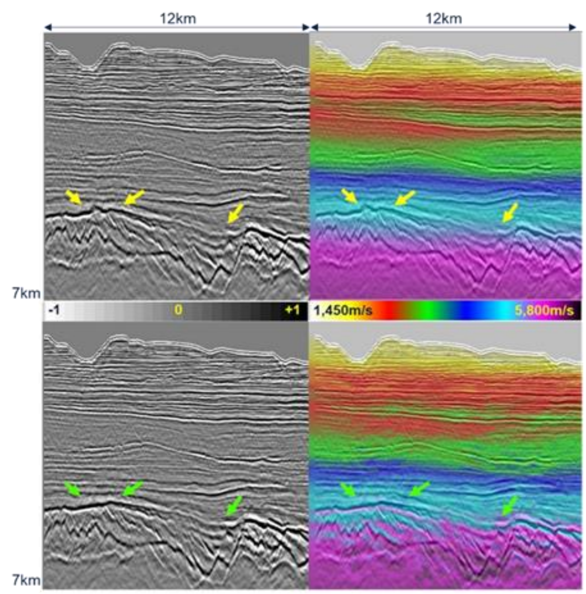

Figure 6: Kirchhoff PSDM stacks and velocity overlays before (top) and after (bottom) DM FWI updates.

Apart from addressing a shallow gas and bottom-simulating-reflector (BSR), deep marine sediment systems are delineated in terms of velocity and lithology after the update (Figure 7). Mid-deep Cretaceous section is also being updated where we see that the number of faults, mainly polygonal, are being updated as slower velocities. The deeper section has similar vertical updates but here we tend to edit these details out as we believe those are artifacts that do not correspond to geological settings.

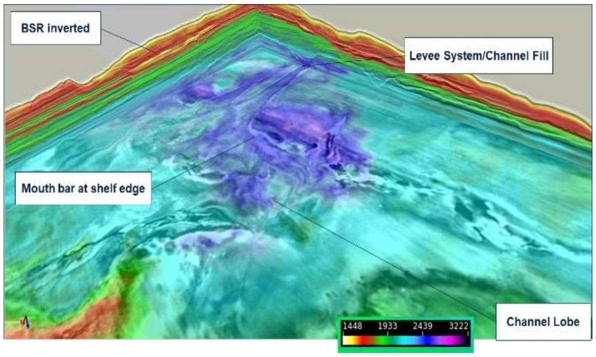

Figure 7: Lithology interpretation aided by high-resolution DM FWI model.

At depth, around the top of continental crust or what is known as economic basement, we see that updates start looking artificial (Figure 6) and mostly mimicking reflectivity due to limited offsets. As these are not contributing to imaging improvements nor gather flatness, we typically opt to scale them back. For model editing we use all the available geological data at our exposure and verify some of the effects of edits on geometrical and AVO attributes.

Due to limitations in dataset acquisition, we often observe that high-resolution models do not alter the stack response; instead, they yield incremental improvements and, overall, more geologically plausible structures. In settings where there is minimal to no well control (such as having only one well in a 25,000 km^2 survey, like the deep-water Raya-1), we validate updates and demonstrate the added value of DM FWI. Figure 8 shows the depth difference between horizons auto picked on tomography and DM FWI solutions at one of the mid-Cretaceous target intervals. We observed variances of -40 m to +80 m and such depth errors can significantly impact the volumetric analysis of potential reservoir.

Conclusions

Pushing the boundaries of technology is an integral aspect of modern exploration. We are often tasked with extracting more information out of legacy data at a reduced cost. DM FWI utilizes both reflection and refraction components of the wavefield and overcomes resolution limitations of conventional model building workflows. In most re-processing projects, we benefit from solid starting models constrained by all available data, resulting in significant updates despite limitations in data regarding offsets and azimuths. However, these updates often require more extensive editing and geological constraints compared to updates from long offsets and full azimuth, along with rigorous quality controls in both the data and image domains. In the case of 2D datasets, we observe that older vintages tend to perform less effectively likely due to a limited offsets and a combination of out-of-spec effects.

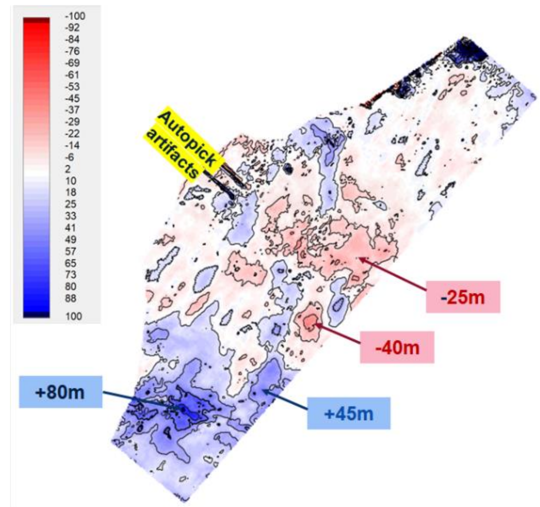

Figure 8: Difference map between mid-Cretaceous target horizon picked on high-res tomography and DM FWI model.

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