Multiparameter full-waveform inversion addressing complex geological challenges in the Gulf of Suez

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Summary

The structural setting of the Gulf of Suez (GOS) and its hydrocarbon discoveries have positioned it as one of the most extensively studied rift basins in the world. The available seismic data, however, is predominantly acquired with limited offsets and narrow azimuths, therefore giving insufficient information to solve the challenges posed by the underlying geology. In this study we show how full-waveform inversion (FWI) in conjunction with newly acquired wide-azimuth, long-offset ocean-bottom node (OBN) data has made it possible to extract earth parameters via data fitting, updating both velocity and anisotropy simultaneously. This workflow has provided fresh perspectives on the geology of the Gulf of Suez.

The utilization of the recent OBN data has facilitated the FWI model building and imaging for both structural and stratigraphic traps (K. Hussein, et al, 2023), thereby enriched our understanding of the existing development fields and transitioned number of leads towards lower risk exploration targets. This is consistent with the recommendations of a forward modeling study performed using a realistic GOS earth model, based on known geological structures and well data (Le Diagon et al, 2020)

Introduction

The Gulf of Suez rift is located north of the triple junction formed by the Gulf of Suez, the Gulf of Aden, and the Red Sea. It is one of the oldest known hydrocarbon provinces in the world. In the modern era, oil was first discovered in 1868 by a French mining company while digging for sulfur. Oil exploration in the Gulf of Suez is defined by a period of prolific discoveries in the twentieth century, particularly between the 1950s and 1980s, followed by a rapid decline. The poor quality of the existent seismic data relates to the limited-offset and narrow-azimuth towed streamer acquisition designs available at the time of acquisition. The quality of the legacy data has hampered more recent exploration efforts to reverse this decline. The study area within the Gulf of Suez is an extensional rift with northwest-southeast fault trends, active in the late Oligocene and early Miocene. Nubia sandstone is a key reservoir rock within the pre-rift section. The sandstone and shale rocks sequence deposited within the syn-rift are overlaid by a tabular and homogenous layer of halite followed by a thick depositional sequence of thin anhydrite, marl, and salt layers known as Zeit formation as shown in figure 1 which was published in 2000 by William J. Billman et al. The layering of various lithologies within the Zeit results in a high impedance contrast which creates severe wavefield attenuation, distortion and generates very strong surface and interbed multiples, which adversely affect the signal-to-noise ratio for the pre-rift seismic images. Moreover, the shallow water depth (10 to 90 m) and the presence of obstructions constitute critical challenges for seismic acquisition and imaging in the region.

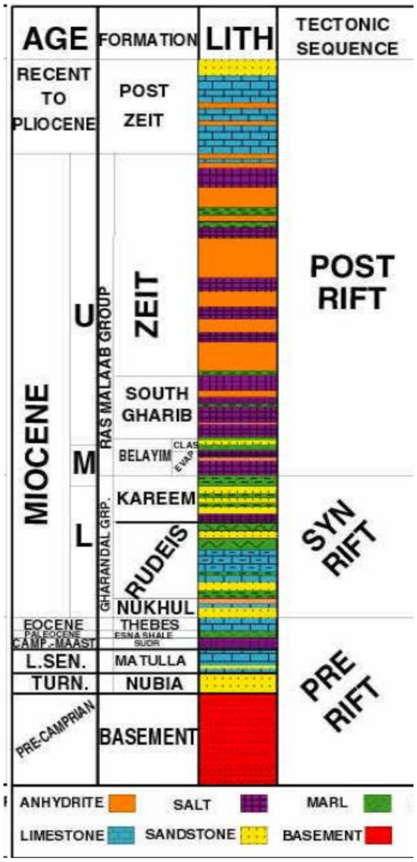

Figure 1: Generalized stratigraphic column of southern Gulf of Suez as published by William J. Billman et al,

Model building with FWI

The key model building tool employed was FWI using the OBN data, following the successes achieved in the complex subsalt settings of the Gulf of Mexico (Vigh et al, 2021), where the utilization of the raw unprocessed seismic records enabled concurrent progress in model building and signal processing. The strong multiple contamination within the target zone and limited reflection incident angles triggered by the fast and layered anhydrites imposed additional challenge for signal processing and limited the success of any early reflection picking based model update tools.

The initial model was built using the large number of wells and the legacy image-based interpretation. The first band of FWI was based upon the lowest useable frequency in the acquired data, which was between 2.5 Hz to 3 Hz. FWI ran to a high number of iterations to address the kinematic errors on model. The early finding showed that the thin anhydrite, halite, and marl sequence within the Zeit resulted in over-predicting the velocity only updates. This initiated the multiparameter FWI efforts where the anisotropy was updated simultaneously with the velocity field. The updated anisotropy is spatially variable and higher in magnitude as shown by the epsilon field in figure 2.

The increase in anisotropy is the result of the thin lithological layering within Zeit formation, and spatial variability in layering intensity can be responsible for the spatial variability in anisotropy.

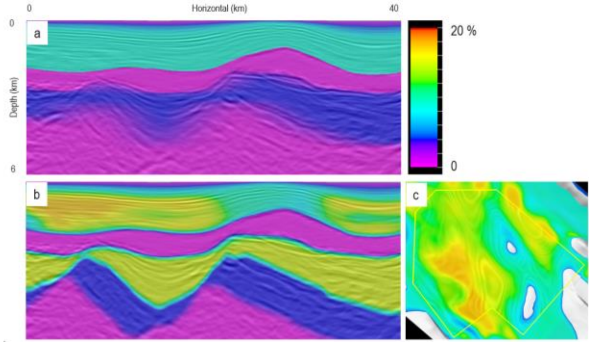

Figure 2: (a) Cross section of starting epsilon, (b) Updated epsilon for the same cross section, (c) Updated epsilon depth slice at depth of 1.2 km

After verifying the validity of the multiparameter FWI at the lower frequencies by checking the data fitting QCs, we adopted a multiscale approach to update the velocity by marching in frequency to 30 Hz maximum, running hundreds of iterations to achieve the desired pre-salt resolution. Such resolution was necessary to map the Nubia in the velocity in addition to the image.

Figure 3a shows the initial model derived from the streamer data with the underlying OBN image and 3b shows the velocity that is derived by FWI, they demonstrate the details added to the earth model especially in pre-salt section. The added details are also demonstrated by the FWI derived reflectivity (Figure 4b) in relation to the initial model's derived reflectivity (Figure 4a).

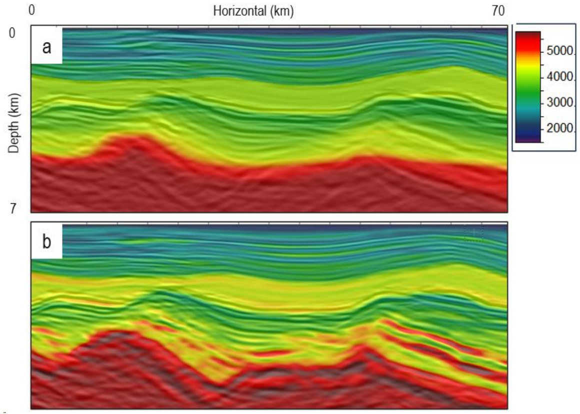

Figure 3. (a) Starting velocity overlaid on RTM image, (b) FWI velocity model overlaid on RTM image

The utilization of the full record including diving waves, refractions, reflections, and multiples within FWI improved subsurface illumination. The FWI derived reflectivity (FDR) (Figure 4b) provided a clean subsurface image that is better compensated for illumination effects (Bing Bai et al, 2022) compared to conventional RTM (Figure 4c) to further help delineate the reservoirs and their terminations to major fault systems.

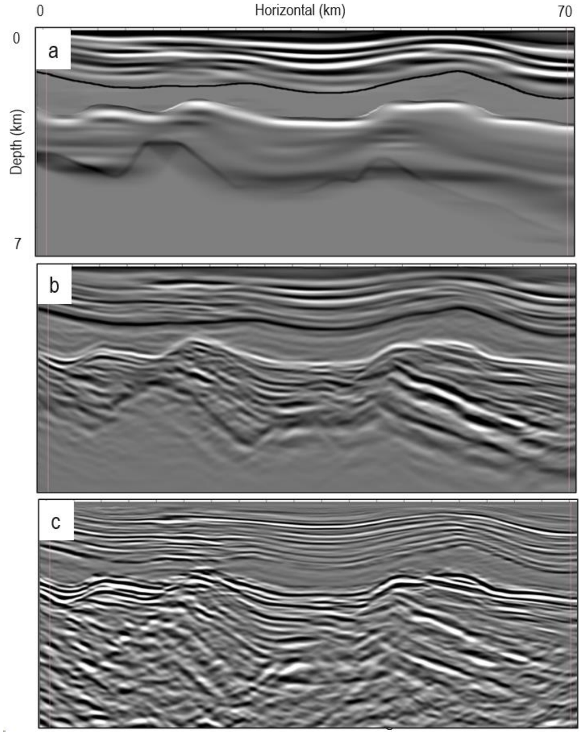

Figure 4. (a) Starting model derived reflectivity, (b) FWI derived reflectivity, (c) RTM image using FWI final model

The final anisotropic earth model expressed the data kinematics by providing best fit between observed and modelled records and was also consistent with well measurements. This was verified by the minimized travel time misfit between the measured check shot's travel times and that estimated by ray tracing through the final FWI model on a local scale. This is demonstrated in figure 5, which shows the reduced misfit in favor of the final FWI model, indicative of more accurate model kinematics. Other model features such as basement structure were verified by gravity inversion aimed to determine basement structure on a basin-wide scale.

The abundance of wells provided calibration points for the initial model, which was achieved by basic petrophysical analysis performed within the distinct geological units, an example of that was the estimation of average velocity for the halite south Gharib formation.

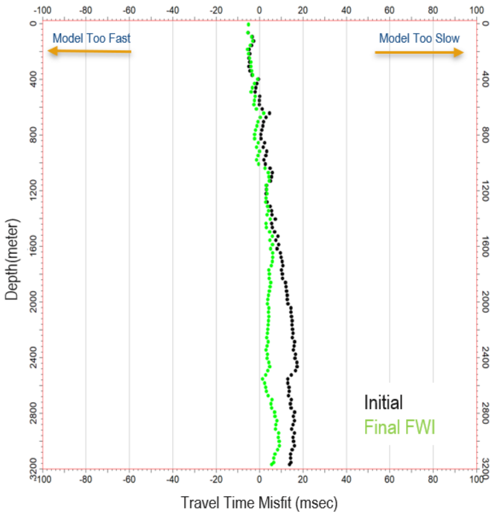

Figure 5. A two-dimensional travel time misfit graph. The vertical axis represents the True vertical Depth at the well location, and the horizontal axis represents the travel time misfit. The black trend represents the travel time misfit computed using the initial model, while the green trend represents the travel time misfit computed using the final FWI model.

In addition, detailed well data integration provided the much-needed quality control during model building stages, through seismic well ties and structural dip QC. This is shown in figure 6, in which well dip meter data were plotted as yellow disks overlaying the seismic images and indicating continual improvement in dip matching between the well measurement and the structural dip from the image generated using the final FWI model.

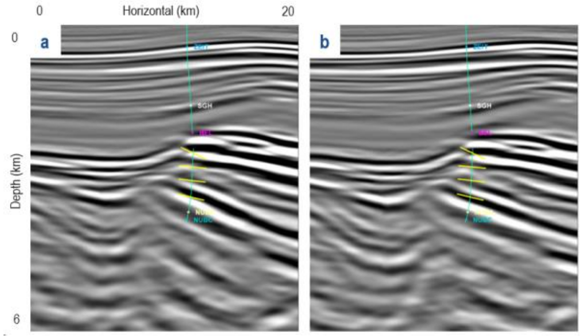

Figure 6. (a) Intermediate RTM Image derived using intermediate FWI model with dip meters overlaid in yellow (b) Final RTM Image derived using Final FWI model with dip meters overlaid in yellow

Conclusion

Improved imaging of both structural and stratigraphic traps, using the new OBN data in conjunction with multi parameter FWI has helped improve the understanding of the existing development fields. Multi Parameter FWI enabled the extraction of the earth parameters by a data fitting technique updating both velocity and anisotropy simultaneously. The accuracy of the derived model was verified using well data.

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