High resolution velocity modelling using Tomography and FWI resolves the pre-Messinian; Nile Delta, offshore Egypt

Abdallah Ibrahim[1] ,Mostafa Salheen[1] ,Mahmoud ElAttar[1] ,Mahmoud Shabana[1], Ivica Mihaljevic[1] ,Mahmoud Ouda[1]; Alaa Khodeir[2]; Ekramy El-Fawi[3] and Mai El-Eony[3]

(1) Schlumberger, (2) BP Egypt, (3) Pharaonic Petroleum Co.

Introduction

The main challenge in imaging the subsurface of the Mediterranean Sea using seismic data is to get the correct velocities at the Messinian and Pre-Messinian formations.

The Messinian geometry at Atoll area of the Mediterranean is characterized by its rapid variations. Its shape ranges from a thin carbonate sheet to a thick pyramid like structure composed of salt and carbonates.

The lithology of the Messinian is also very variable, in some few locations it is purely salt, in many other locations it is composed of dirty salt, clean salt, carbonates and shale with different contributions are found in the same area within a few tens of meters of the Messinian formation.

In this paper, we will present a robust workflow for velocity model building and depth imaging of the Mediterranean around Atoll area where we implemented full waveform inversion (FWI) along with tomography and different seismic migration algorithms.

We will show the details of the FWI workflow and the use of adjustive FWI to overcome the common problems of cycle skipping especially when the very low frequencies of the data suffer from low signal to noise ratio.

The data of study area is recently acquired in 2017 using a broadband acquisition, we will thus show the impact of the broadband acquisition on the results of FWI and tomography, and the uplift that the broadband processing can have on the final image.

The most important finding is also how the integration of well data, geologic information and new technologies like FWI can collaborate to open new plays in the Mediterranean & consequently new opportunities.

Discussion

Distinguishing between the different compositions of the Messinian and deriving its velocity accurately has been a major challenge to the whole industry over the past decades. It is not uncommon to see final seismic data products with distorted images of the pre-Messinian section where the Messinian geometry is clearly imprinted deeper down.

Companies generally focused their drilling efforts away from the poorly imaged areas which form the major part of the Mediterranean. This is a huge but untapped market for oil and gas production if a solution for these poor imaging issues can be found.

To resolve such a complex geology like that of the Messinian and image the subsurface details beneath it, a set of requirements should exist. Simply we need recorded seismic data that effectively reach the subsurface and illuminate it, a broadband to exist in the deep targets, and we need to be able to accurately repeat the seismic acquisition experiment in our computers to produce a correct image of the subsurface. This last step implies that an accurate earth model should be estimated.

Conventional data processing and imaging approaches suffered from very limited data below Messinian with only near angles being recorded. Also, frequency loss can be observed in many of these conventional approaches both on the low and high side of the spectrum making the deep events ringy, noisy and difficult to interpret. When we add to these factors the absence of accurate velocity model we end up with an imprint of the complex Messinian character beneath the Messinian and a poor image in general.

Seismic acquisition and data conditioning

The seismic acquisition of the study area was conducted in 2017 near Atoll field using a Geostreamer broadband narrow azimuth seismic acquisition, maximum offset for the acquisition was eight kilometers. This offset range is relatively large in comparison to the older seismic data existing in the area, thus it allows data coming from deeper subsurface to be recorded.

The acquisition also involved dual sensor receivers: a hydrophone and geophone that were added together to remove the effect of receiver ghosts. Adaptive source deghosting was additionally applied to the data to remove the source ghost. The deghosting properly corrects the wavelet phase, increases the temporal bandwidth, and provides a better broadband data set for further demultiple and imaging.

This adaptive deghosting approach we used was introduced by (Rickett 2014). It is a data-dependent method that does not rely on strong assumptions about water velocity or depth of the source and receivers.

The data conditioning also comprised multiple removal using 3D SRME, data regularization and additional noise attenuation to prepare the data for depth imaging.

Depth imaging workflow

The depth imaging workflow started by building an initial model of the earth, which was calibrated to check shot velocities from the existing wells in the area. Initial anisotropy parameters were estimated after we studied the well markers tie with the seismic data at different well locations. Eta parameter which was picked on the time migrated gathers was used to fine tune the Thomsen Epsilon and Delta parameters exploiting the important Thomsen relationship: Eta = (Epsilon – Delta) / (1+2*Delta).

As a start for the velocity model update workflow a tomography update was done focusing on the post Messinian section below the water bottom. The tomography approach used here for velocity model update is after (Woodward et al. 1998). Steering filters (Clapp et al. 2004; Bakulin et al., 2010) were used utilizing the geologic dip measured from the seismic images to constrain the direction of updates and speed up the convergence of the model to an optimum solution.

Geobody modelling

The next step was to begin capturing the Messinian section velocity in our model. An automatic geobody modelling approach was utilized to capture the Messinian based on its seismic attributes. Here we exploited the fact that Messinian amplitude signature on the seismic images is different from the rest of the section and using a combination of different attributes we captured the top and base of the Messinian. An average velocity was inserted in the Messinian Geobody followed by a second tomography update. The idea is that we wanted to include the Messinian average velocity in the model to help the tomography and full waveform inversion to capture its actual velocity in the subsequent updates. (figure 1)

After the Messinian Geobody modelling, we went into two parallel routes for velocity model update:

a. A conventional CIP tomography workflow which involved 6 tomography iterations.

b. FWI route which involved the use of both FWI and tomography to build the model.

In the next section, we will review the details of the FWI route.

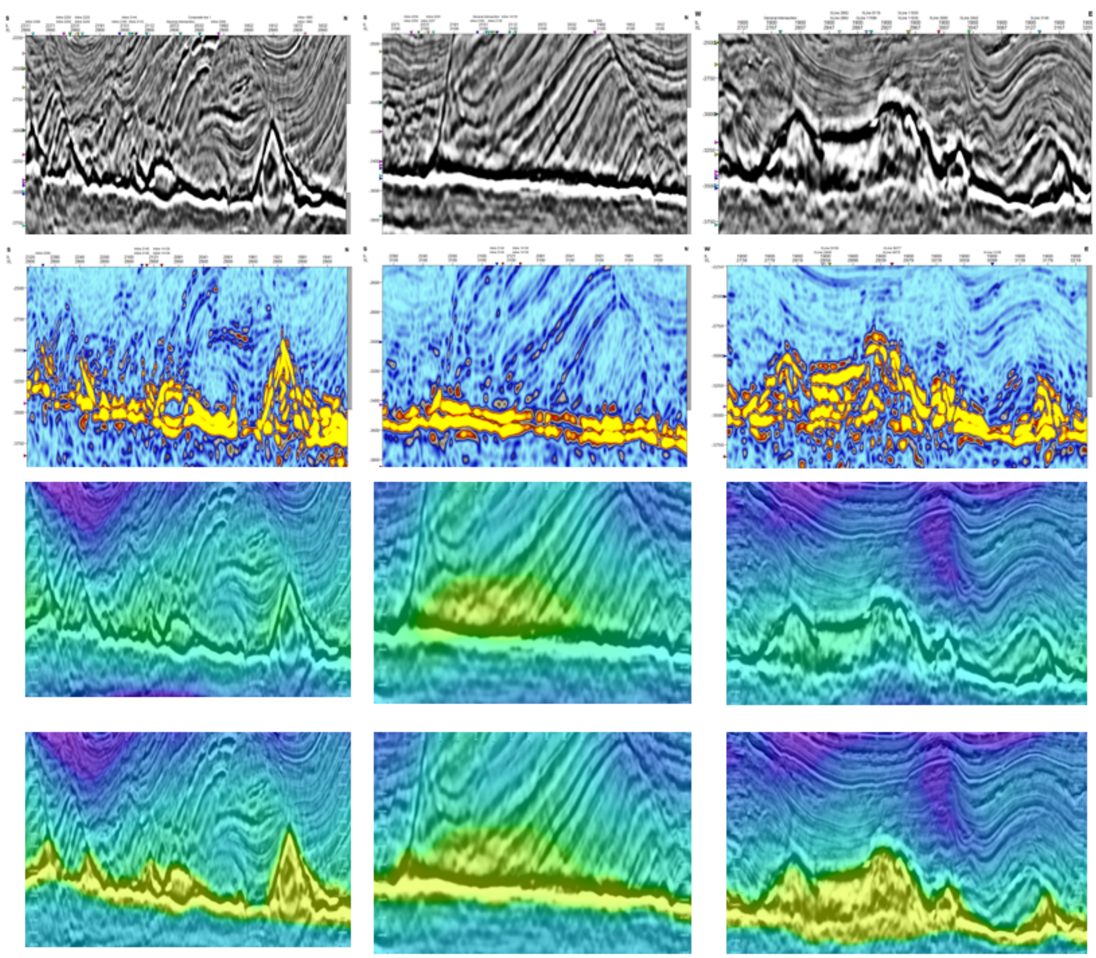


*figure 1: **a**. different salt geometries in the area, thin sheet, pyramid like structure and complex dirty salt **b**. seismic attributes used to extract the Messinian Geobody **c**. Velocity model before Messinian velocity insertion **d**. velocity model after Messinian velocity insertion*

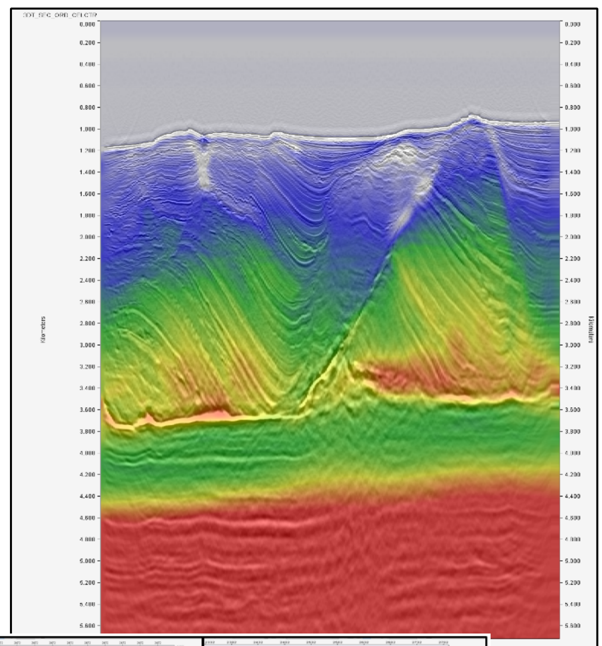
Full Waveform Inversion (FWI)

Full waveform inversion (FWI) is essential to capture the short wavelength variations in the Messinian, in this area after we did the geobody modelling it was time to start FWI.

The conventional FWI algorithm begins by forward modelling synthetic shot gathers using the current velocity model, the synthetic shots are compared to the real shots in the same locations were the difference between the actual and synthetic shots is called the misfit function. FWI is based on iteratively updating the model by minimizing the least square (LS) misfit functional between the real and synthetic shots. The approach commonly suffers from cycle skipping problems especially when the initial model is too far from the real earth. The Synthetic and real shots can cycle skip and the FWI solution converges to a wrong model (Jiao 2015)

An adjustive approach for FWI misfit function (Jiao et al. 2015) was used. This objective function is based on the travel time shift as a misfit function. Using this objective function FWI can be used to correct the erroneous background model, and therefore mitigate cycle-skipping issues and improve the robustness of FWI.

The first few iterations for velocity update in each frequency band were executed using the adjustive objective function followed by the conventional least squares difference misfit approach. The input gathers to FWI are the raw gathers with minimal processing to remove spurious noise. We used raw gathers to ensure that no process has altered the data character or changed its phase and to maximize the use of refractions and diving waves.



The first phase of FWI was mainly focused on inputting the refractions and early arrivals into the FWI misfit function computations and muting everything else to avoid unnecessary complications and the risk of cycle skipping while the model is still not optimum.

FWI velocities estimated from the refractions clearly showed a lot of improvement. The shallow hazards below the water bottom were captured in the velocity model where we see a lot of shallow pressured gas zones with their characteristic low velocity (figure 2)

Multiple attenuation was applied on the FWI gathers and deeper reflections were gradually included in the later FWI updates from the water bottom until the base of the Messinian.

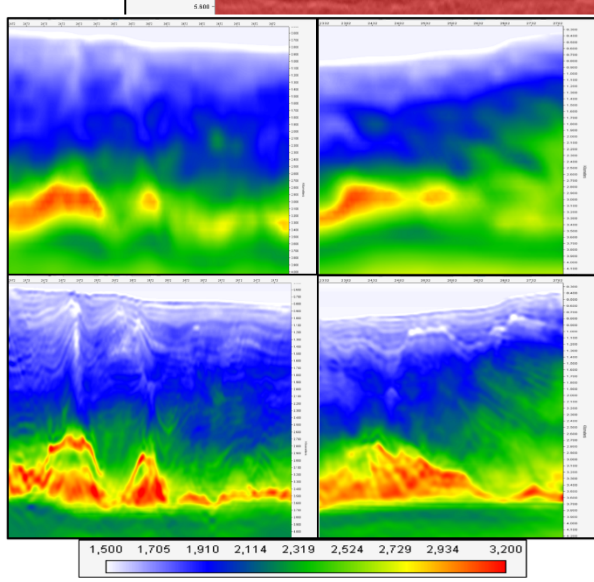


figure 2: detailed velocity captured by captured by refraction FWI

The Messinian formations were captured with a high degree of accuracy (figure 3) we started to see layering and variations inside the Messinian and above it, which resolved the instability and distortion of the seismic data below Messinian. Depth migration after FWI shows a lot of uplift over the old data using tomography alone.

Velocity updates after FWI

After FWI, additional tomography updates were done to stabilize the velocities in the pre-Messinian section. With the FWI accurate velocity updates in the shallower parts till the Messinian, the ray tracing for tomography and migration became more accurate, this pushed the tomography updates to converge quickly to an optimum update.

Well Tie

As mentioned before the initial model was tied with the checkshot velocities from the wells in the area. The long wavelength trend from the seismic velocity was matching the trend from the wells however the fine details were still missed. The FWI velocity update showed a nice match of the fine details with the well data although no well information was incorporated during the FWI velocity updates part. This gave some confidence about the integrity of the update as well as the anisotropy parameters used.

Conclusion

Figure 3 ***a.*** *legacy velocity* ***b.*** *FWI velocity, notice the fine details captured in the Messinian*

Most of the ingredients for accurate seismic imaging were included in our approach for this study area; Seismic data with broadband and relatively long offsets, processing and imaging technologies adequate to get a good image in addition to the well information and the experience in the area geology and anisotropy.

The acquisition coupled with adaptive deghosting and the other signal processing steps ensured that the data contains less ringing, and a good bandwidth in the deep section. Tomography and full waveform inversion worked together to build the background model and update the fine details of the Messinian. We clearly see an improved pre-Messinian section with less imprint of the Messinian structures and more details about the actual geology there.

References:

Bakulin, A., M. Woodward, Y. Liu, O. Zdraveva, D. Nichols, and K. Osypov, 2010, Application of steering filters to localized anisotropic tomography with well data:80th Annual International Meeting, SEG, Expanded Abstracts, 4286–4290, http://dx.doi.org/10.1190/1.3513765.

Clapp, R. G., B. Biondi, and J. F. Claerbout, 2004, Incorporating geologic information into reflection tomography: Geophysics, 69, 533–546, http://dx.doi.org/10.1190/1.1707073.

Jiao, K., D. Sun, X. Cheng, and D. Vigh, 2015, Adjustive full waveform inversion: 85th Annual International Meeting, SEG, Expanded Abstracts, 1091–1095, http://dx.doi.org/10.1190/segam2015-5901541.1.

Rickett, J., 2014, Successes and challenges in 3D interpolation and deghosting of single-component marine-streamer data, successes and challenges in 3D interpolation and deghosting of singlecomponent marine streamer data: 84th Annual International Meeting, SEG, Expanded Abstracts, 3599–3604, http://dx.doi.org/10.1190/segam2014-1159.1.

Woodward, M., P. Farmer, D. Nichols, and S. Charles, 1998, Automated 3D tomographic velocity analysis of residual move-out in prestack depth migrated common image point gathers: 68th Annual International Meeting SEG, Expand ed Abstracts, 1218–1221, http://dx.doi.org/10.1190/1.1820113.