A case study using FWI to image pre-Messinian target in the East Mediterranean Sea

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Summary

Imaging of a pre-Messinian target in the Eastern Mediterranean Sea remains a challenging task. Recent gas discoveries, in the Eastern Mediterranean Sea, have increased interest in enhanced imaging beneath Messinian salt layers. To adequately image the pre-Messinian, various challenges need to be addressed, including correctly illuminating the sub-salt portion. The Eastern Mediterranean's illumination issues are largely caused by a complex combination of shales and salt structure. The Messinian layer, in this region, is very heterogeneous, and it consists of a mixture of salt and clastics known as 'dirty salt,' which presents another challenge for velocity model building (VMB). In order to improve pre-Messinian imaging, a VMB workflow solution, including FWI, has been proposed in this paper to resolve the Messinian salt layers and post-Messinian carbonates. The workflow has been applied to data acquired using a multi-sensor streamer and a triple source acquisition configuration, recently in the area.

Introduction

In the last few years, worldwide interest in the offshore Eastern Mediterranean region has grown due to its hydrocarbon potential. There have been several discoveries off the coast of Egypt, Cyprus, and Israel. There are several challenges for accurately imaging the pre-Messinian. However, the key challenge is the existence of the Messinian salt layer and its varying complexities in this region. Furthermore, since the pre-Messinian layers might be complicated, the process of building the optimum depth velocity models is constrained by the acquisition geometry and the availability of well data. Hence, to overcome these challenges, it involves both optimizing acquisition parameters and building accurate geological models. The Eastern Mediterranean area is sparsely populated with multi-azimuth streamer surveys; most are narrow azimuth. A lack of azimuthal diversity can degrade the imaging of sub-salt targets even when after successfully obtaining optimum velocity models using existing datasets.

Complex interaction of shales and salt are primary reason behind observed illumination issues in the Eastern Mediterranean region. The Messinian layer, across this region, can be a mixture of salt and clastics, termed as ‘dirty salt’. This makes this layer very complex and heterogenous and thus velocity model building is a challenging task. In this paper, we are focusing on a couple of blocks of Eastern Mediterranean Sea, acquired using multisensor streamer triple-source seismic data. Optimal velocity model building for depth imaging involves the application of complementary imaging technologies to mitigate assumptions in any single process (Whitmore and Crawley, 2012, Brandsberg-Dahl *et al*., 2017). Using this strategy, we demonstrate a solution for the complex post-Messinian carbonates and Messinian salt layers, in order to improve the pre-Messinian imaging and reduce uncertainty in the seismic amplitudes.

Velocity Model Building Methodology in Eastern Mediterranean

The Velocity Model Building (VMB) workflow used for the work presented in this paper has been shown in Figure 1 as flow chart. Various key layers addressed during different stages of VMB workflow are highlighted in a schematic diagram on top right corner of the figure. The water velocity layer was the first layer to be addressed in the VMB. During seismic acquisition, temperature-salinity (TS) measurements were recorded at different locations across the survey, and a TS driven 1-D function was used for the water layer velocity profile.

In the absence of sonic well information, a smooth Dix interval velocity model (Dix, 1955) was constructed from a PSTM interval velocity field and implemented as the starting isotropic model for the post-salt region. Several isotropic reflection tomography updates were performed before introducing anisotropy in the velocity model building for this layer as it is critical to get an accurate velocity profile before evaluating optimum anisotropy parameters. To further improve the accuracy in the post-salt section, several ray-based wavelet-shift (Sherwood *et al*., 2011) gridded tomography passes were performed using Tilted Transverse Isotropy (TTI).

As mentioned earlier, complexity in the Messinian layer is the main challenge in imaging the pre-Messinian section. Detrital sediments from the Nile Delta break the distribution of salt in the two major basins, the Herodotus, and the Levant (El-Bassiony *et al*., 2018). The salt body geometry shifts from horizontal bedding in a compressive regime along the basin margin to a more diapiric system closer to the Nile Delta's cone. The salt layer shows intra-salt reflectivity away from the diapiric area, indicating complex heterogeneities within this layer. The VMB workflow needs to address these variations within the layer to obtain an accurate model for the Messinian layer, which is key in imaging the Pre-Messinian section. The Messinian layer can be divided into two types for the area of study presented in this paper. The

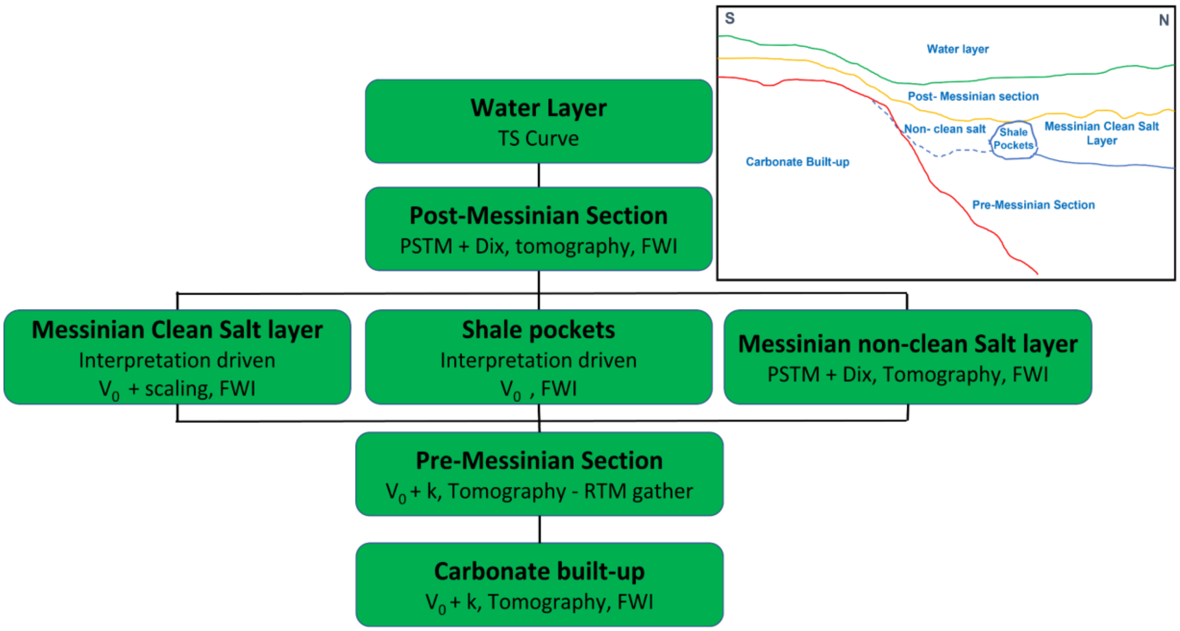

***Figure 1** VMB Workflow. Top left corner shows schematic diagram highlighting key geological layers which have been targeted at different stages of the VMB workflow presented as a flowchart.*

first type is termed as clean salt area, identified by presence of clear top and base salt interpretation. Second type is heterogeneous due to intrusion by an inflow of shales, softening the velocity contrast at the top Messinian boundary. The layer model was built for the first type, utilizing top and base salt interpretation. Despite the heterogeneity in the salt layer, a constant salt velocity provides a simpler structure of the base of salt (El-Bassiony *et al*., 2018) and a good average background velocity to assist further tomographic updates. A constant velocity of 4500 m/s was used in this instance. A further spatially varying salt velocity was obtained by picking the errors at the base salt moveout on gathers. On the other hand, for the second type of interpretation-driven model building was not an appropriate choice as the velocity contrast is softened. In a few locations in this layer, shale pockets have also been identified, for which the model was built by scanning different velocity scenario testing.

Using the wavelet-shift tomography model as an input, Full Waveform Inversion (FWI) was used to further improve the post-Messinian and Messinian layers. When scale-lengths of homogeneities, such as those found within the complex Messinian layer, cannot be represented by rays and Snell's Law, waveform-based back-propagation methods, such as FWI, provide the resolution in the model that ray-based back-projection approaches cannot. FWI iteratively solves a model using numerous repeated waveform propagation modeling steps as the velocity model evolves. Data with a maximum frequency of 12 Hz were used to develop an accurate FWI velocity model during this model building phase, leading to an improvement in the pre-Messinian imaging.

The background velocity in the pre-Messinian layer can be built using V_0 (starting velocity) and k (gradient) model. The starting velocity, in northern part of the survey presented, ranges anywhere between 2000 to 2400 m/s with a gentle gradient. Whereas the starting velocity increases to 3200 m/s to 4200 m/s in the presence of carbonates build-ups that are located underneath the base Messinian towards the southern edge of the area. The velocity inside the carbonate built-ups progress at a much higher gradient compared to the pre-Messinian layer reaching up to 6000 m/s. Strong reflectors at the top and within the Messinian layer generate a series of interbed multiples that were clearly noticeable in the sub-Messinian region. Hence, angle gathers produced by Reverse Time Migration (RTM) were used for ray-based tomography in the pre-Messinian model building sequence. Since two-way wave energy can appropriately map internal multiples in the image domain, RTM angle gathers exhibited less apparent interbed multiple energy. As a result, the residual moveout picking, using RTM angle gathers, was less impacted by internal multiples from the Messinian layer, maintaining an accuracy in the pick constraints used for the inversion, and resulting in a model that further improved the pre-Messinian imaging.

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Data Example

The seismic data, presented in this paper, was acquired as a part of a multi-client campaign in the Eastern Mediterranean Sea, offshore Egypt, with water depths ranging from 700 m to 2300 m. The survey was acquired using a triple-source configuration and sixteen 8025m long multi-sensor streamers separated by 75 m. The wavefield separation process was performed to produce upgoing wavefield. The data was further processed using a standard pre-processing workflow including full 3-D denoise and demultiple processes. In clean salt area of the survey, converted wave energy generated within salt layer is observed. Converted wave attenuation workflow using 3-D acoustic modelling (Kumar *et al*., 2018) was also implemented for these areas.

Figure 2 shows an inline section example of the uplift achieved by the proposed velocity model building phase.

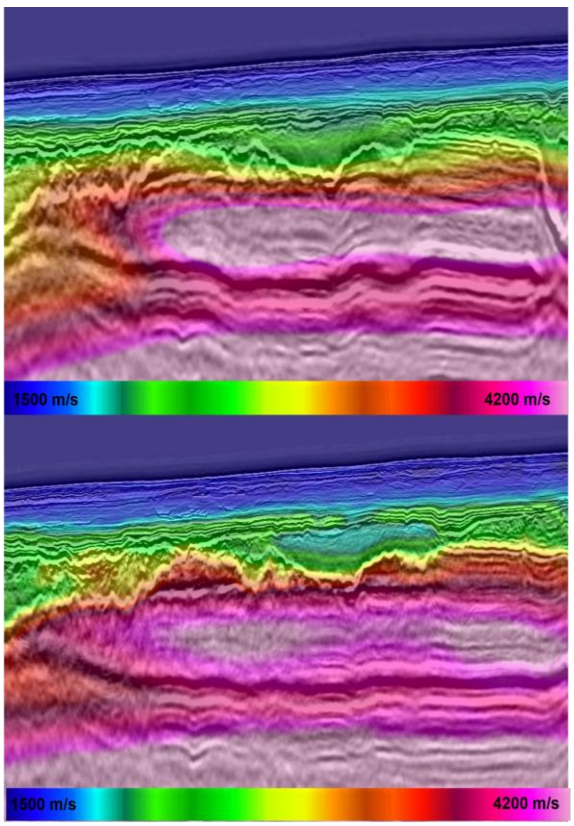

Figure 2 *Inline showing the uplift through the velocity model building workflow. Top image is showing velocity overlaid on its corresponding migrated stack at early stage in VMB workflow whereas the bottom image is showing the final velocity model overlaid with its corresponding migrated stack*
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The upper image of the figure shows the velocity model from an early stage in the VMB workflow overlaid on its corresponding migrated stack. The distortion of events in the pre-Messinian section is evident due to unresolved overburden complexity in the velocity model. The bottom image, showing the final velocity model overlaid on the corresponding migrated stack, demonstrates how the proposed VMB workflow successfully captured the overburden complexity very well, simplifying the structure and improved the seismic image in the pre-Messinian section.

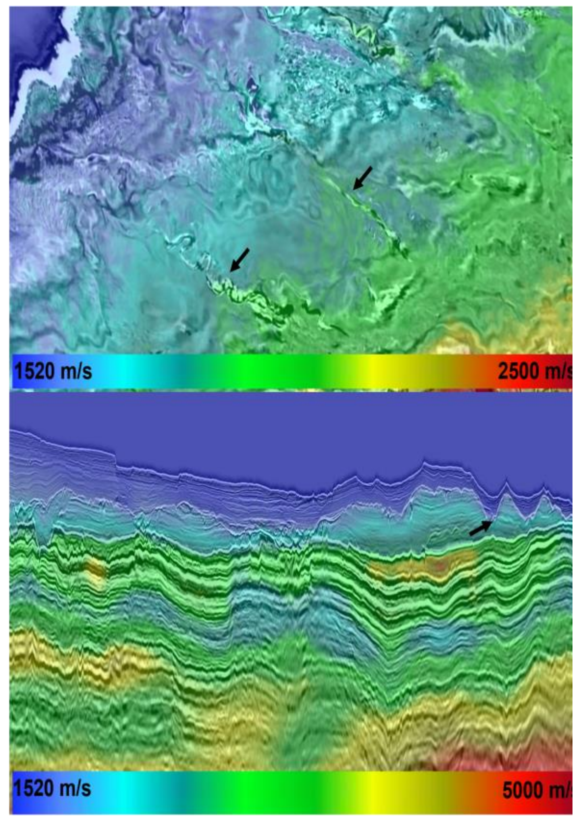

Figure 3 *Depth slice (Top) and Inline (bottom) of the final velocity model overlaid with its corresponding migrated stack. Small channel features have been accurately delineated.*

Figure 3 illustrates an example of a depth slice (top) taken from the post-Messinian section and an inline section (bottom) of the final velocity model overlaid on the Kirchhoff migrated seismic section. As shown by arrows on depth slice, shallow channels in the post-Messinian section are clearly delineated by the velocity model obtained by proposed workflow, thanks to FWI. The lateral velocity variation in pre-Messinian and Messinian sections has been well resolved by the VMB workflow as seen in the inline section.

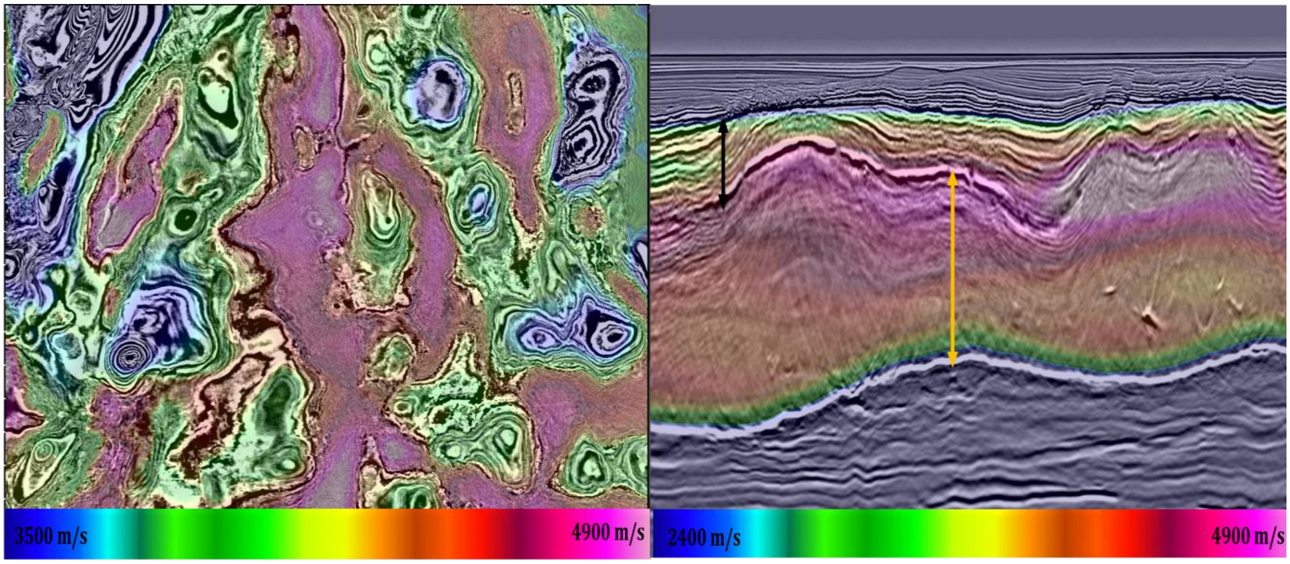

Figure 4 *Depth slice (left) and Inline (right) of final velocity model overlaid with its corresponding migrated stack. Heterogeneity in the Messinian salt layer has been well captured by the VMB workflow.*

Figure 4 demonstrates an example of a depth slice (left) and inline section (right) of the final velocity model overlaid on its corresponding migrated seismic section in a clean salt area. The depth slice is taken through the Messinian layer, which shows that the velocity variations within this layer have been very well constrained to the Messinian layer. In this part of the survey one can observe a thick layer (shown by black arrow) on top of the transparent and clean salt layer (shown by orange arrow). These sediments are within the Messinian layer and mostly made up of various salts, which have a velocity much higher than the post-Messinian layer but lower than clean halite salt layer. The inline section also shows simplified base salt and pre-Messinian section, suggesting that the velocity variation within the Messinian has been optimally derived by the proposed workflow.

Conclusions

Uncertainties in the imaging of the pre-Messinian targets can be mainly attributed to the Messinian layer complexity in the Eastern Mediterranean Sea. In this region, the Messinian layer is heterogenous and complex, and to obtain the optimum pre-Messinian image, it is vital to resolve the complexities of this layer. By incorporating technology like Full Waveform Inversion (FWI) and RTM angle gathers, the proposed VMB workflow has been successful in capturing most of the post-Messinian and-Messinian complexities, resulting in improved imaging of the pre-Messinian target.

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