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Imaging Pre-Messinian Targets In The Eastern Mediterranean Using FWI And RTM

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ABSTRACT

The Eastern Mediterranean Basin has emerged as a region of considerable hydrocarbon prospectivity, underpinned by well-established petroleum systems across multiple stratigraphic intervals. Proven reserves in Jurassic and Cretaceous formations, as well as Pliocene deep-marine sandstones sourced from the Nile Delta, highlight the region's potential for both oil and gas accumulations. Additionally, the identification of Pre-Messinian carbonate buildups—analogous to the prolific Zohr gas discovery offshore Egypt—suggests that similar high-potential plays remain underexplored (Roberts & Peace, 2020).

Despite this promise, imaging Pre-Messinian targets remains a significant geophysical challenge due to the presence of the heterogeneous Messinian evaporite sequence. Although the post-Messinian sedimentary section is generally thin in the West Delta, the Messinian salt exhibits substantial lateral and vertical velocity variations, introducing strong seismic velocity contrasts in the overburden. These contrasts adversely affect wavefield propagation, leading to distorted seismic images and reduced illumination of subsalt targets (Kumar et al., 2022).

Effective imaging of the Pre-Messinian interval requires addressing two principal challenges: accurate characterization of salt-body geometry and velocity heterogeneity, and mitigation of illumination issues related to the complex topography and internal variability of the salt. This demands a robust depth velocity model building (VMB) process, supported by advanced imaging technologies. Full Waveform Inversion (FWI) and Reverse Time Migration (RTM) have demonstrated substantial value in this context. FWI enhances the resolution of subsurface velocity models by iteratively minimizing the misfit between recorded and modeled seismic data, while RTM enables accurate imaging in complex geological settings by accounting for multi-pathing and wavefield complexity (Brandsberg-Dahl et al., 2017).

We present data examples from recent seismic acquisition programs in the Eastern Mediterranean that have implemented these techniques, with encouraging results. Tailored acquisition geometries and high-end processing workflows have improved the fidelity of subsalt imaging, revealing structural and stratigraphic details within Pre-Messinian targets that were previously obscured. These enhanced seismic images provide interpreters with critical information to delineate potential reservoir facies, including deep-marine clastics and carbonate buildups, thereby reducing exploration risk and supporting more informed drilling decisions (Kirkham et al., 2023).

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INTRODUCTION

The East Mediterranean region represents one of the most tectonically and geologically dynamic areas of the world. Lying at the intersection of the African, Eurasian, and Arabian plates, it is shaped by a complex history of rifting, subduction, and plate convergence (Robertson, 1998). In this context, the offshore domains of Egypt and Cyprus are particularly significant, both geodynamically and as emerging hydrocarbon provinces.

The northern margin of Egypt and the southern offshore of Cyprus lie along the transition from a passive continental margin to an active subduction zone near the Cyprus and Hellenic arcs. This tectonic setting has given rise to deep sedimentary basins such as the Herodotus and Levant Basins (Fig. 1), which host thick sedimentary successions including the prominent Messinian evaporites (Montadert et al., 2014).

The Messinian Salinity Crisis (5.96–5.33 Ma) led to massive salt deposition across the East Mediterranean due to isolation from the Atlantic and subsequent extreme evaporation (CIESM, 2008). In the offshore regions of Egypt and Cyprus, the Messinian salt layer can exceed 1.5–2.5 km in thickness. This evaporitic layer plays a dual role: it acts as both a seal for hydrocarbon reservoirs and a mobile unit that complicates subsurface imaging due to its low and laterally variable seismic velocities (Bertoni & Cartwright, 2005).

One of the primary geophysical challenges in the region is velocity model building (VMB), which is critical for seismic imaging beneath salt. The high contrast in acoustic velocity between salt and surrounding sediments, combined with the salt's complex geometry (e.g., diapirs, salt tongues), leads to multipathing, wavefront distortion, and poor signal-to-noise ratios (Chopra & Marfurt, 2007). These issues hinder accurate depth migration and trap delineation.

The interaction between the Messinian salt and interbedded clastic sediments including significant clay-rich intervals—poses major challenges to seismic illumination (Darwish et al., 2024). These clay intrusions, often emplaced during or after salt movement, have complex geometries and variable velocities that exacerbate seismic wave distortion. When clay layers intrude into or overlay salt structures, they introduce sharp acoustic impedance contrasts and anisotropic velocity fields, leading to ray scattering, attenuation, and severe multipathing. This results in poor seismic illumination, especially beneath or adjacent to salt bodies where energy is deflected or absorbed, creating shadow zones and reducing signal coherence. The combined effect of ductile salt flow and clay deformation generates irregular overburden velocity fields, which degrades the accuracy of pre-stack depth migration and hinders reliable velocity model building. Consequently, subsalt and intra-salt imaging become uncertain, necessitating advanced methods like Full Waveform Inversion (FWI) and illumination-guided acquisition design to recover high-fidelity subsurface images.

In this region, traditional velocity analysis is often inadequate, requiring advanced approaches like Full Waveform Inversion (FWI) and Reverse Time Migration (RTM). Moreover, salt tectonics drives the formation of mini-basins and thrust structures, further complicating the seismic velocity field.

Accurate velocity models are essential for reducing drilling risk and improving reservoir characterization. In areas like the Zohr Field (Egypt) and Aphrodite Field (Cyprus), exploration success has depended heavily on improved imaging beneath salt layers. Therefore, understanding the distribution, thickness, and dynamics of Messinian salt is fundamental to any exploration strategy in the region.

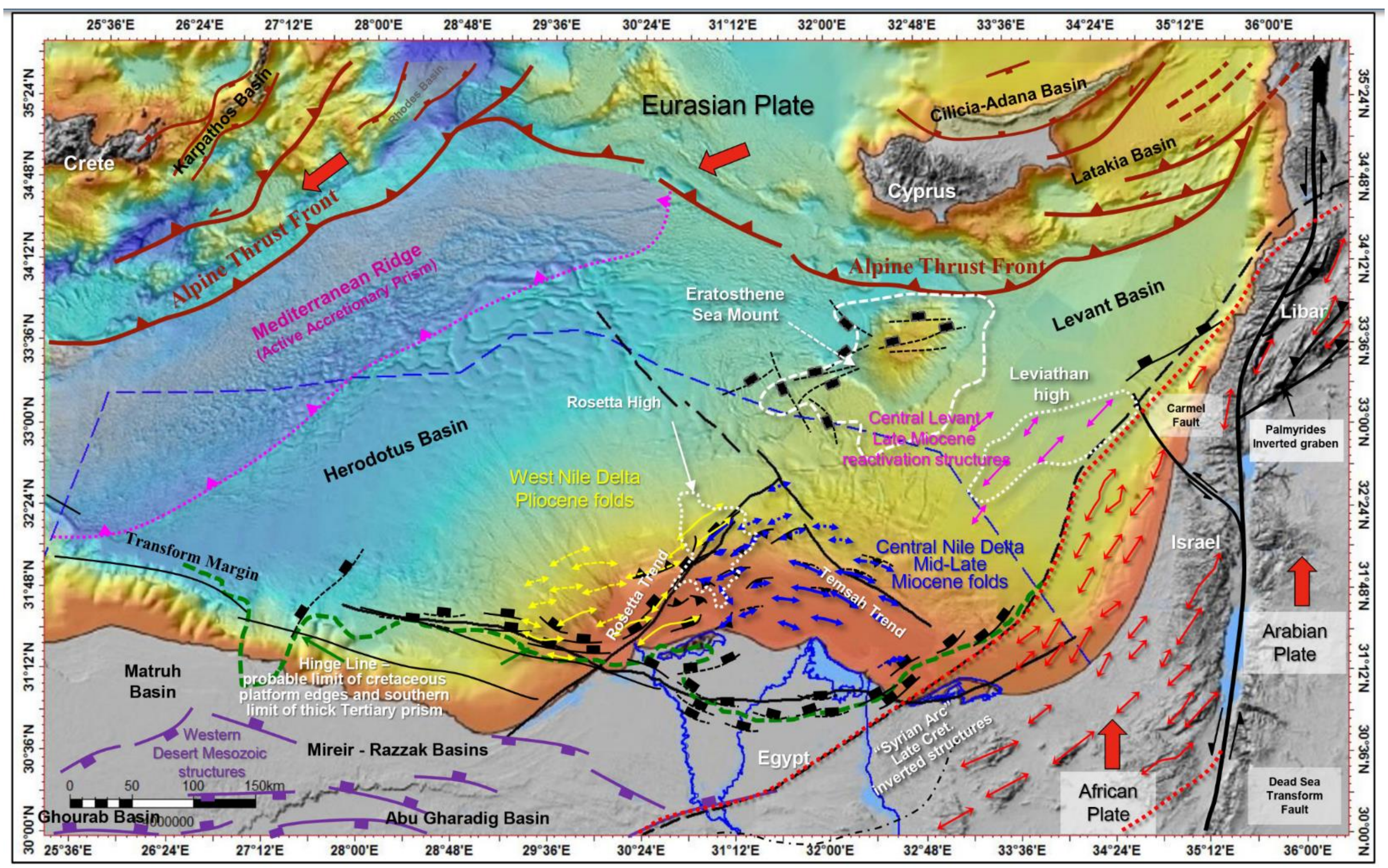

Fig. 1 - Eastern Mediterranean structural elements map showing the two major basins (Levant and Herodotus), Egyptian Ministry of Petroleum and Mineral Resources website.

VELOCITY MODEL BUILDING (VMB) WORKFLOW

The Herodotus Basin, a key exploration area in the Eastern Mediterranean, presents significant challenges in Velocity Model Building (VMB) due to the complex overburden, including Messinian evaporites, and intricate Pre-Messinian targets. These challenges are primarily driven by the heterogeneity of the Messinian salt and post-Messinian sedimentary structures such as buried channels, mud diapirs, and intra-Messinian clastics, which complicate both velocity model construction and seismic imaging.

Fig 2 shows the Velocity Model Building (VMB) workflow adopted for the work presented in this paper. A schematic diagram in the left top corner highlights various key layers targeted at different stages of the VMB workflow.

An initial velocity model for the post-Messinian section was constructed using a smoothed Dix interval Pre-Stack Time Migration (PSTM) approach, based on limited well control from the Kiwi and Sidi-Barani wells. The model, initially calibrated to a medium to long-wavelength resolution, was insufficient for capturing lateral velocity variations associated with buried channels and mud intrusions. To address this, Full Waveform Inversion (FWI) was applied, significantly improving the velocity resolution and enhancing the imaging of key stratigraphic features (Zou et al., 2010).

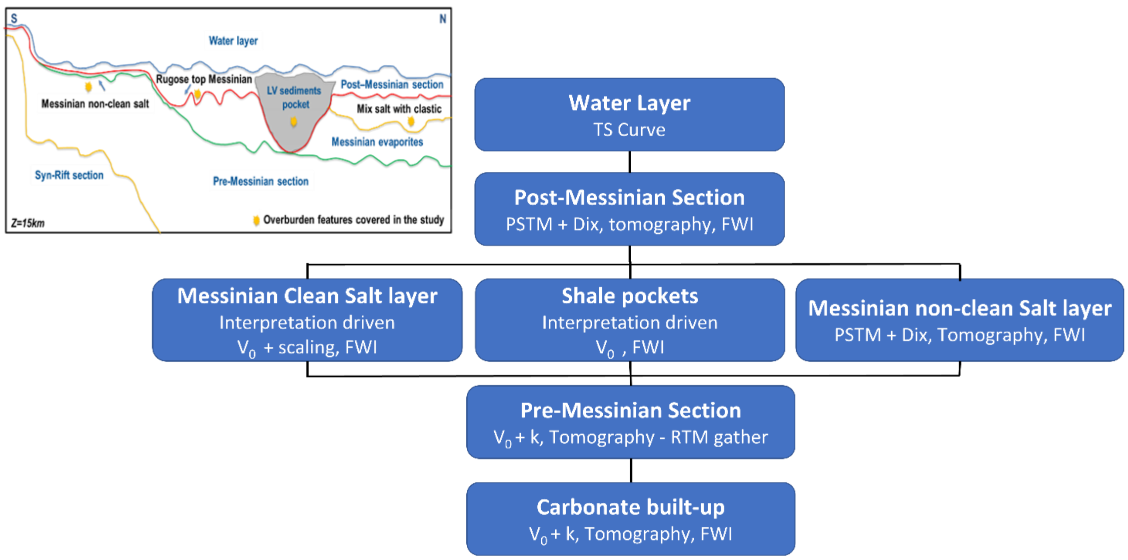

Fig. 2 - VMB Workflow. Top left corner shows schematic diagram highlighting key geological layers which has been targeted at different stages of the VMB workflow presented as flowchart

The Messinian evaporite layer exhibits complex geometries and internal heterogeneities, transitioning from horizontally bedded salt in the compressive regime to more diapiric structures in the vicinity of the Nile Delta cone (El-Bassiony et al., 2018). Seismic analysis and borehole data indicate that the salt consists of transparent halite layers, interspersed with reflective clay interbeds that influence wave propagation. A 3D average velocity model for the Messinian salt, constructed through reflection tomography updates, was used as an initial model, with average velocities ranging from 3600 m/s to 4500 m/s depending on the sedimentary content of the salt. These velocities were refined using reflection tomography and refraction-based FWI, which improved the gather flatness and overall model resolution, allowing for more accurate delineation of the salt geometry.

The complexity of the Messinian evaporite layer increases towards the basin margins, particularly along the shelf where the salt thins to velocities as low as 3200 m/s (Darwish et al., 2024). This thin layer induces velocity distortions and complicates wave arrival time and azimuthal behavior. To address these challenges, multiple passes of reflection tomography, combined with constrained FWI, were applied to refine the velocity model and correct residual errors in the Pre-Messinian section. This multi-step process led to improved velocity accuracy and enhanced subsalt imaging, particularly in areas affected by strike-slip tectonics and salt deformation (Reston et al., 2002).

Another notable challenge was the presence of shallow, low-velocity clay pockets formed by Miocene turbidites, which intruded above the salt. These geo-bodies exhibit velocities ranging from 1700 m/s to 2000 m/s and pose a significant challenge for velocity model integration due to their weak reflectivity. Velocity analysis, followed by reflection tomography, was used to integrate these clastic pockets into the depth model, further enhancing velocity resolution and imaging of the complex overburden (Sherwood et al., 2011).

FWI was particularly effective in improving the imaging of the post-Messinian and Messinian layers, providing high-resolution updates by iteratively minimizing the misfit between observed and modeled data. FWI's ability to resolve long-wavelength features, often missed by ray-based methods, was crucial in enhancing the imaging of both salt structures and subsalt reservoirs. In shallow water depths, FWI benefited from refracted and diving waves, while in deeper waters, limited streamer length necessitated reliance on low-frequency reflected waves for high-frequency updates (Zou et al., 2014).

Pre-Messinian imaging faced significant challenges due to complex overburden geometries, faulting, and tectonic activity in the Mediterranean Ridge area. Variable illumination caused by the rugose top salt presented difficulties in obtaining clear images of Pre-Messinian targets. To address this, Reverse Time Migration (RTM) was implemented, offering significant advantages over traditional Kirchhoff Pre-Stack Depth Migration (PSDM) methods. RTM handles complex wave paths and high-velocity contrasts, providing clearer images of the base salt and Pre-salt reflectivity. Additionally, RTM's ability to decompose data into pre-stack angle gathers proved effective in overcoming the challenges posed by internal multiples, which were prevalent in the shelf areas.

RTM-based angle gathers provided robust datasets for subsequent ray-based tomography, improving velocity model updates and leading to more accurate imaging of Pre-Messinian targets. The velocity profile of the Pre-Messinian section exhibited a gentle gradient, with velocities ranging from 1900 m/s to 2400 m/s beneath the salt. In the presence of carbonate buildups beneath the salt, velocities increased to between 3200 m/s and 4500 m/s, with steeper gradients observed in deeper waters (Manzi et al., 2016). Further image enhancements were achieved by combining RTM with FWI and ray-based reflection tomography, which improved both subsalt imaging and structural interpretation in complex geological settings.

VMB EXAMPLES

In this study the seismic data examples were acquired as part of TGS multi-client campaign in the Eastern Mediterranean Sea, covering areas offshore Egypt, Cyprus, Greece and Lebanon. The data library comprises both 2D and 3D surveys with water depths ranging from 50 m to 3700 m (Fig. 3). Recent 3D surveys, offshore Egypt, were acquired using three different acquisition configurations ranging from 12 x 10 025m (150 m streamer separation) to 16 x 8 025m (75 m streamer separation) with triple-source configuration. The upgoing wavefield was isolated through a wavefield separation process applied to the multi-sensor recordings. The data was then processed using the latest pre-processing workflow which included full effective 3D denoise and de-multiple techniques. Long streamer of 10km length was used in acquiring the 2D data in the area.

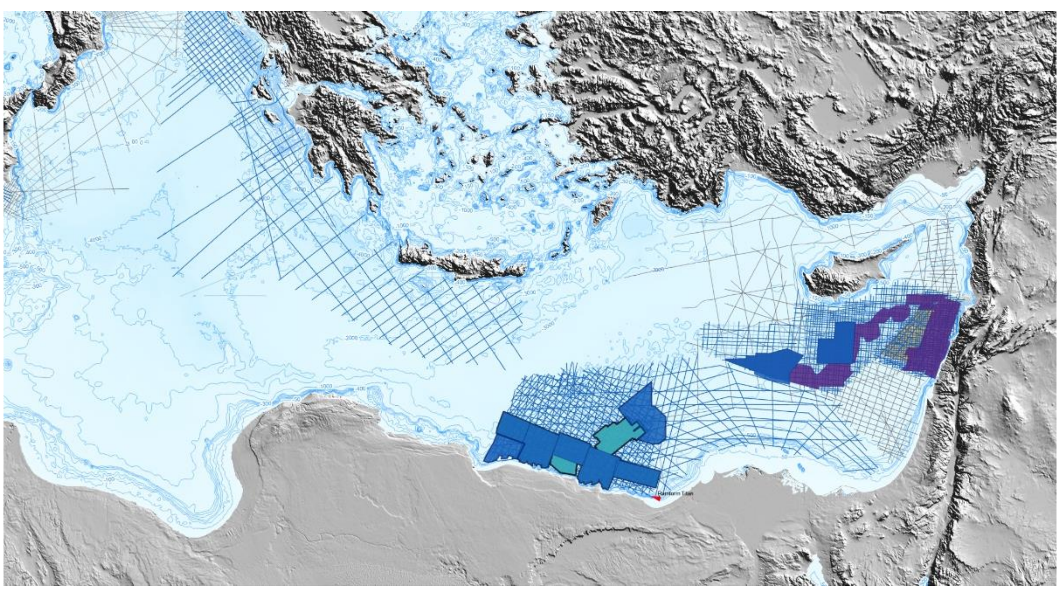

Fig. 3 – Eastern Mediterranean map showing the TGS 2D and 3D multi-client data library.

Post Messinian

Figure 4 shows two depth slices (a and c) and two inline sections (b and d) of the final velocity model superimposed on the Kirchhoff migrated image. Panels 4a and 4b show the depth slice and inline section through the post-Messinian interval in the deep basin area, while panels 4c and 4d show the equivalent images for the shelf area. Arrows highlight regions where the velocity model obtained through Full Waveform Inversion (FWI) effectively delineates the shallow channels in the deep basin as well as the shallow, potentially carbonate features. The enhanced velocity resolution in the shallow section significantly improves the accuracy of both the imaging and structural geometry of the pre-Messinian section.

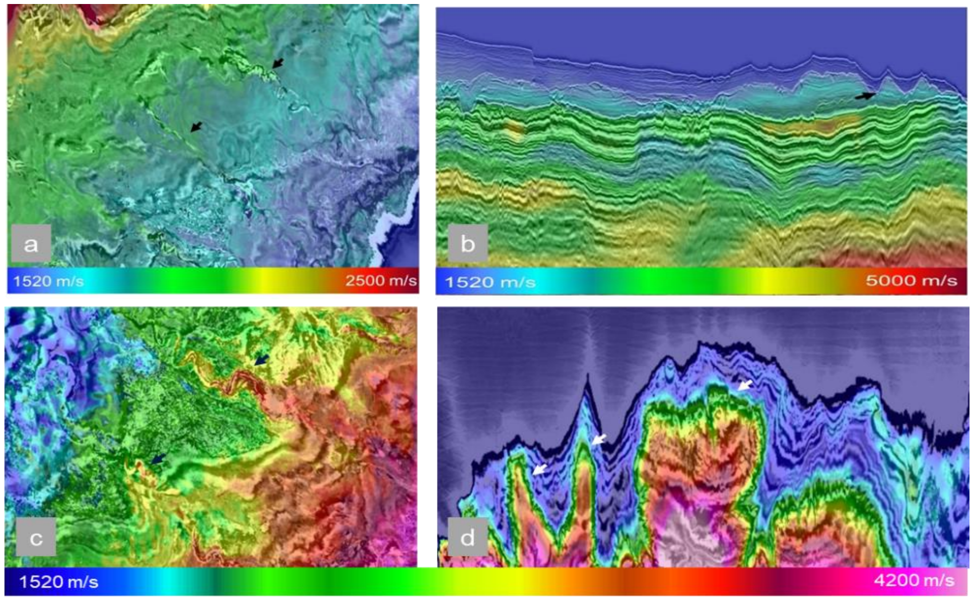

Fig. 4 – Examples of post-Messinian channels, offshore Egypt. Depth slice (a and c) taken through post-Messinian section and Inline (b and d) of the final migrated Kirchhoff image overlaid with the final velocity model. The proposed VMB workflow managed to capture the heterogeneity in the post-Messinian section in shelf and deep basin areas.

Messinian Evaporites

Figure 5 presents an example of a thick Messinian salt layer, showing depth slices (a, b, and c) and inline sections (d, e, and f) of the migrated image, each overlaid with the corresponding velocity models. The figure compares the three models: the initial background velocity model, a constant salt velocity flood, and the final FWI- derived variable salt velocity model. In this example, a thick sediment pocket, likely representing the Rosetta formation (indicated by the white arrow), is formed on top a clean halite salt layer (marked by the orange arrow). These sediments, primarily composed of anhydrite interbedded with thin clay layers (Helaly, 2019), exhibit velocities lower than the clean halite salt layer and higher than the post-Messinian section. This example demonstrates how the VMB workflow effectively resolves velocity variations within both the Messinian and post-Messinian intervals. The improved FWI velocity model also enables more accurate interpretation of the base salt and the underlying pre-Messinian structure, as shown by the dashed lines.

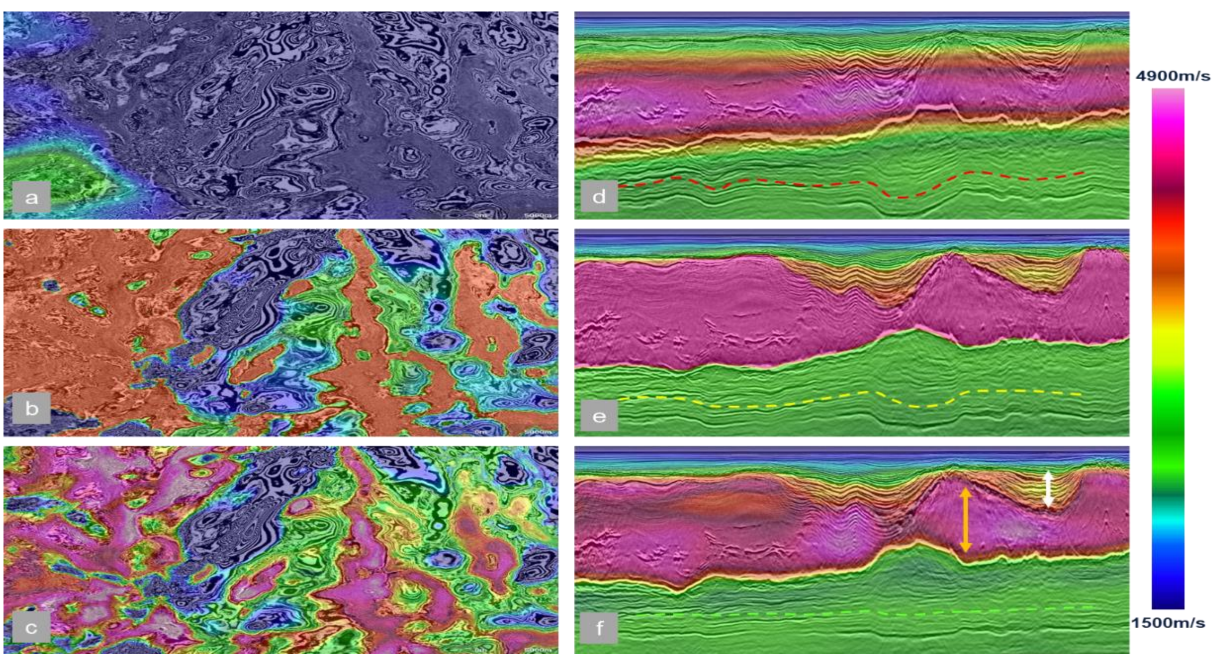

Fig. 5 – Examples of non-clean, thick salt layer. Depth slice (a, b and c) taken through Messinian section, comparison between initial background model (a), constant salt velocity flood (b) and the final FWI variable salt velocity model (c) overlaid on the corresponding migrated image. The same comparison for Inline (d, e and f) of the final migrated image overlaid with the corresponding velocity model.

Pre-Messinian challenges

Figure 6 illustrates an inline section showcasing the complex Messinian salt geometry in the Mediterranean Ridge region. The Kirchhoff migrated depth image is shown in Figure 6b, and the corresponding RTM image is displayed in Figure 6c. Both images were obtained by migrating using the same velocity model, which is also overlaid on the Kirchhoff migrated image in Figure 6a. The arrows in the images indicate how RTM more accurately delineates the base of the salt and pre-Messinian reflectors by effectively handling complex wave paths, in contrast to the limitations of Kirchhoff migration. RTM also generates a significantly cleaner image, particularly at the base of the salt (BOS). In this example, the overburden model was built using reflection tomography and FWI, while RTM was employed to refine the salt geometry and update the pre-Messinian velocities (Darwish et al., 2024).

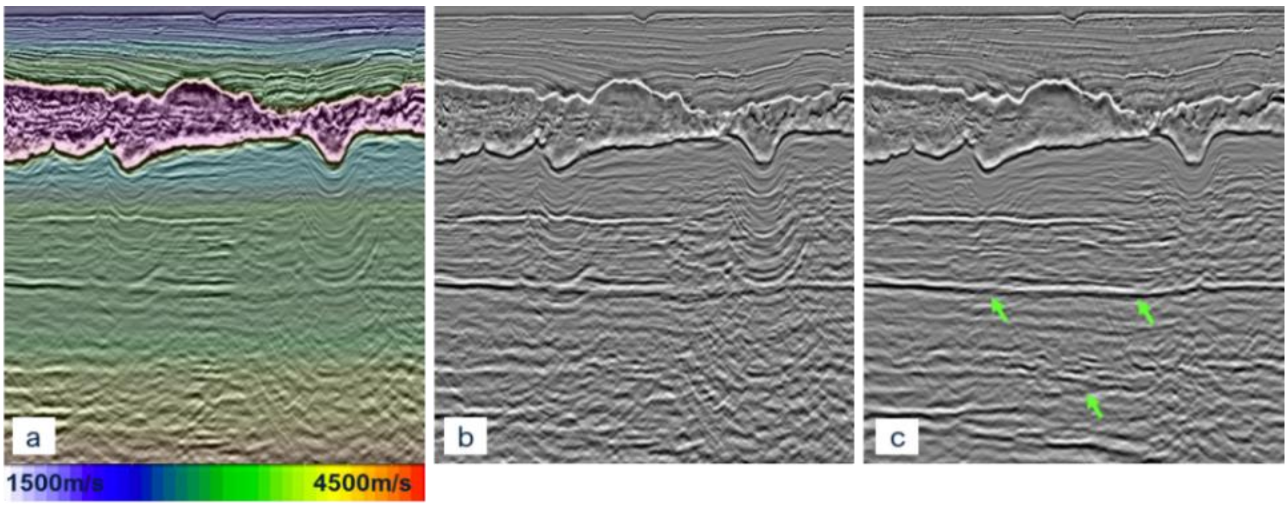

Fig. 6 – Example of an inline with the final velocity model overlaid with the Kirchhoff depth migrated stack (a). Comparison between Kirchhoff Depth image (b) versus RTM image (c). Clear image improvements of the pre-Messinian section can be observed (as shown by arrows).

CONCLUSIONS

In the Eastern Mediterranean Sea, the Velocity Model Building (VMB) challenges are categorized into overburden and pre-Messinian imaging challenges. The Messinian layer in this region is highly heterogeneous, making it essential to resolve the velocity complexities of the overburden to achieve optimal imaging of the pre-Messinian layer. Additionally, variable illumination requires migration techniques capable of managing complex wave paths in complex structures. The proposed VMB workflow, which includes FWI and Reverse Time Migration (RTM), has proven to be effective in addressing these complexities and successfully captured the velocity details of the post-Messinian and Messinian layers and enhances the imaging of pre-Messinian targets.

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