Introduction

The Sidi Moussa survey is located offshore Morocco in water depths of 100-1500 m. The overburden geology is complex with strata dipping in different azimuths the topography of the due to a rugose water bottom is very rugose, with canyons and shallow channels throughout the survey area. The deep target has a multi history structure with variable thickness of carbonates overlying the zone of interest (Figure 1). The consequence of these complexities, combined with vintage narrow-azimuth (NAZ) acquisition, is an overall poor seismic response resulting in significant uncertainty in target interpretation and low signal-to-noise ratio. A different approach attempted not only in terms of acquisition method, but also an advanced processing workflow to improve the target imaging and illumination.

Figure 1 (left) Play cartoon highlighting the Nour structural complex and the Lower Jurassic – Triassic target interval. (Right) Dip section through existing Sidi Moussa 3D survey. Note steeply dipping reflectors of the Nour structural complex, the thickness of the middle and upper Jurassic carbonates at this location, and the poor quality of imaging in the lower Jurassic section.

To achieve a better image and reservoir characterization in the zone of interest, Genel Energy acquired three surveys with three different azimuths over the Sidi Moussa discovery in 2018. It is well-known that the benefits of multi-azimuth acquisition include not only improved illumination, increase in signal-to-noise ratio, and enhanced amplitude fidelity, but also a reduction in uncertainties associated with the earth model derivation and final depth migration. Figure 2 shows the comparison of the Kirchhoff depth image from two different acquisition azimuths, where illumination differences at target depth can clearly be seen.

Figure 2 Kirchhoff depth migration stack of dip azimuth 142° (right) and that of strike azimuth 52° (left). Clear differences in the illumination can be seen.

To fully benefit from the advantages of multi-azimuth data, a novel model building workflow was devised. This included multi-azimuth refraction-based full waveform inversion (FWI) to enhance the shallow velocity (Vigh et al., 2016), and high-resolution multi-azimuth common image point (CIP) tomography (Woodward et al., 2008), followed by Q-tomography (Cavalca et al., 2011), to further improve the amplitude reliability.

We present how this workflow was used to build a high-quality velocity model subsequently used by Q-Kirchhoff depth migration (QKDM) and reverse time migration (RTM) to provide an improved image that reduced uncertainty in target interpretation in this area. Figure 3 highlights the model building workflow.
Full waveform inversion

The presence of water-bottom canyons and shallow channels in the survey result in a complex overburden velocity. It is, therefore, important to build an accurate shallow velocity model to avoid distortion of the structure underneath.

FWI is a data-driven method for generating high-resolution velocity models. The algorithm iteratively updates the subsurface earth models to reduce the misfit function, measuring the difference between the recorded seismic data and the simulated waveforms. Acquisition is a key factor that can have a large impact on the FWI results. Comparisons of FWI using a single azimuth and multiple azimuths clearly demonstrated the advantages of multi-azimuth acquisition with better illumination than a single narrow azimuth as shown in Figure 4.

In this survey, we ran FWI using data from all three azimuths. An initial vertical transversely isotropic model was built from a legacy model. We performed two frequency bands of refraction-based FWI: the first at a peak frequency of 6 Hz using a combination of adjustive and least-squares (LS) FWI. Adjustive FWI (Jiao et al., 2015), which has a traveltime-based objection function, was used to mitigate cycle-skipping issues and improves the FWI robustness with an inaccurate initial model. The second band had a peak frequency of 8 Hz and used least-squares FWI only. Figure 5 shows the inline and depth slice QC of the initial model and the final FWI updated velocity and total velocity difference between FWI and initial model. The shallow low-velocity canyons and channels are clearly highlighted in the updated velocity model. Adjustive and LS FWI using diving waves was also successful in updating the high velocities in deep areas related to the Jurassic carbonates.

Figure 4 a) FWI updated velocity using single azimuth. b) Three azimuths (right). It is clearly shown that multi-azimuth FWI gave better and more robust updates with less acquisition imprint.

Multi-azimuth velocity model building

The updates from FWI were limited to depths above 6 km due to the penetration depth of the diving waves and maximum acquisition offset (~ 7 km). CIP tomography was applied to extend the update for the deeper target velocities. The additional azimuth information allows us to better constrain our multi-azimuth tomography to produce a detailed velocity model with high degree of accuracy. The three azimuths were preprocessed separately for tomographic velocity model building. Regularization was applied for individual data sets separately to remove the acquisition footprint effects.
All three azimuth sectors were iteratively prestack depth migrated with Kirchhoff migration for the model building loops. These image gathers were then individually picked to measure multivalued residual moveout (RMO). All three sets of RMO picks were provided to CIP tomography to update the model. Different weights were applied on individual azimuths based on pick quality related to the varying illumination to improve the update quality. The CIP tomography used a damped least-squares solver at progressively finer scale lengths, with a preconditioning-smoothing operator being applied at each scale length to improve the solution convergence. (Woodward, et al. 2008). Structural dip information was used as a constraint to ensure that the update conformed to geology (Bakulin et al. 2010). This process was iterated until a satisfactory velocity model was achieved. In this case, a total of five iterations were performed to produce a detailed tilted transversely isotropic velocity model with Q-tomography that was used to update a Q model in the 5th iteration. As shown in figure 6, the resulting model was highly conformant with structure and provide a significant uplift in deep target.

**Advanced multi-azimuth Q-KDM and reverse time migration**

To fully utilize the benefits of multi-azimuth data, a high-resolution Q-KDM and multi-azimuth RTM image were produced. The Q-KDM was generated for individual azimuths separately and the individual azimuth sector migrations showed space-variant differences in stacking response. The azimuth sectors illuminate different areas of the zone of interest with varying signal-to-noise ratios. Ideally, the optimal data set will be a combination of the best stacking response and highest signal-to-noise ratio data regions from each azimuth sector, thereby producing an optimized final stack volume.

To take advantage of the multi-azimuth data sets and improve the efficiency of RTM migration, all shots were combined as supershots to produce a high-resolution 50-Hz RTM image. The final multi-azimuth RTM image shows clear uplift in terms of data continuity, visibility, and sharpness of the
dipping events compared with the single-azimuth RTM image, particulary in areas of complex geology as shown in Figure 7.

**Figure 7** RTM with single-azimuth (left) compared to multi-azimuth RTM image (right). Multi-azimuth RTM shows a significant improvement in imaging the structurally complex target zone due to improved illumination.

**Conclusion**

We presented a successful model building workflow that fully exploited the advantage of multi-azimuth acquisition, using FWI and CIP tomography to produce a high-resolution model from shallow to deep target. The resulting images using advanced migration algorithms are demonstrably far superior to the vintage seismic data and provide a more suitable data set for structural interpretation, amplitude variation with offset inversion and reservoir characterization. Figure 8 shows this comparison with the legacy image and model.

**Figure 8** Legacy model and KDM image (left) compared to new model and Q-KDM (right). The model better conforms to the geology, leading to significant improvement in the imaging of the key Jurassic horizon, which benefits from both the multi-azimuth acquisition and advanced multi-azimuth model building techniques.

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**References**


