

From an old seismic acquisition to rock properties, a successful journey in the Middle East

Introduction

Imaging the subsurface of the Arabian Gulf is particularly challenging due to its very shallow-water environment, hard seafloor and complex near-surface geology. This combination tends to generate significant multiple contamination that masks primary reflections and strongly impacts their amplitude-versus-incidence-angle (AVA) behavior. In the absence of an accurate subsurface image and reliable seismic attributes, field development becomes complex and relies heavily on well information and large-scale geological models.

Recent advances in seismic imaging have nevertheless demonstrated that these challenges can be overcome, enabling accurate subsurface imaging in the region (Damianus et al., 2023; Chen et al., 2025). However, these impressive results were obtained from nodal acquisitions benefiting from high fold, wide-azimuth coverage, and dual-sensor (geophone and hydrophone) recordings, which facilitate the separation of primary energy from multiples.

In contrast, our case study relies on a 1995 towed-streamer acquisition covering a 170 km² area over a four-way-closure domal structure. The survey was acquired using a dual-source, dual-streamer configuration with a maximum offset of 3 km. However, several lines used a shortened 1.2 km streamer, while others operated in undershoot mode due to pre-existing surface facilities. These acquisition constraints further complicated earlier processing efforts, leading to poor imaging results characterized by insufficient near-angle coverage of shallow reflectors and strong acquisition footprints. To overcome these limitations, an advanced seismic imaging workflow was implemented to deliver a final seismic image suitable for inverting both acoustic impedance (I_p) and V_p/V_s ratio using an elastic stratigraphic inversion. This result is essential to support continued field development and ensure production sustainability.

An iterative multiple attenuation

With a water depth of about 20 meters, the demultiple stage was the most critical step of the seismic data pre-processing workflow. Following comprehensive denoising and source wavelet correction through designature and 3D deghosting, a dedicated demultiple workflow was applied. The absence of near offsets (minimum offset of 120 m), combined with the shallow water depth, resulted in the water-bottom primary reflection not being recorded. However, this information is essential for conventional demultiple techniques such as surface-related multiple elimination (SRME). To overcome this limitation, multiple imaging was performed to reconstruct the water-bottom reflectivity from information contained within the multiples themselves (Poole et al., 2022). This least-squares imaging of the shallow reflectivity was then used to build a short-period surface-related multiple model (Pica et al., 2005). To address longer-period surface multiples, SRME was applied using a muted water-bottom dataset. Once the surface related multiple models were generated, the main challenge became their adaptive subtraction. In a geological setting characterized by predominantly flat layers, dip discrimination between primary and multiple is minimal. In addition, with a shallow seafloor, moveout discrimination between primaries and multiples is also very limited, making multiple removal and primary reflections preservation particularly difficult.

To overcome this challenge, a reflectivity model was constructed from well information. The field benefits from a dense well coverage, providing strong a-priori information. Sonic and density logs were used to compute acoustic impedance and derive reflectivity at each well location. The integration of well-derived reflectivity with the main geological horizons enabled the construction of a synthetic reflectivity model free of multiples. This reflectivity model was then demigrated to the acquisition geometry to generate an initial primary model in the data domain. It was also used to generate internal multiple models, with multiple generators identified through Vertical Seismic Profiling (VSP) analysis. Adaptive subtraction was then performed by jointly adapting primary and multiple models, both

surface-related and internal, facilitating the separation of recorded wavefields. The resulting dataset was constructed by summing the adaptively matched primary model and the residual signal, i.e., the portion not explained by either the primary or multiple models. This residual predominantly contains primary energy that was insufficiently represented in the initial primary model.

An iterative approach was consequently implemented: the dataset obtained from the first iteration was migrated to enhance primary focusing and suppress residual noise, then demigrated to update the primary model. Additional residual demultiple was applied in the image domain to further refine the primary model. Demigration ensured the correct kinematics across all offsets of the primary model. Throughout the iterative process, well-tie quality control was systematically performed to ensure that multiples were effectively attenuated without compromising primary reflections. In addition to zero-offset well ties, AVA behavior was carefully monitored to verify amplitude preservation (figure 1). As the velocity model plays an important role to ensure good focusing of energy in the image data and correct kinematic of the demigration in the data domain, a velocity model was built and refined in parallel with this demultiple work.

Detailed velocity model

The gentle anticline forming the reservoir of this field has a relatively simple structure with minor spatial velocity variations expected. However, vertical variations are much more complex, with alternating fast and slow layers. This complexity not only generates multiple reverberations but also produces residual moveout if the velocity is not properly inverted.

The dense well information was used to build an initial velocity model. This was followed by tomography performed on data with optimized demultiple processing, allowing us to update both the velocity and the anisotropy. The resulting model was then used as the initial model for Acoustic Full Waveform Inversion (FWI). Despite limitations in the recorded data - namely narrow azimuth and limited offset - the availability of a reliable initial model ensured a stable FWI convergence, enabling us to update the velocity field up to 15 Hz. For this FWI, data with limited preconditioning was used without muting to benefit from the full wavefield and notably the primary and multiple reflections. The

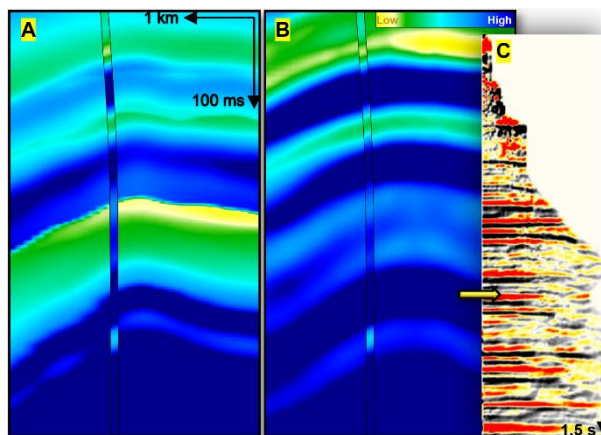


Figure 2: a) Legacy velocity; b) 15 Hz FWI velocity model; c) PSDM CDP

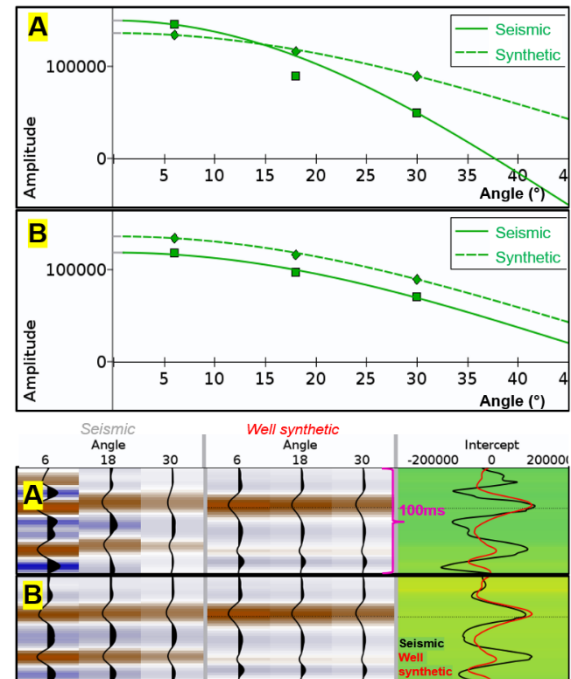


Figure 1: AVA fit QC using well synthetic data. A represents an initial demultiple test where B is the final demultiple output

resulting velocity model exhibits vertical variations that are well aligned with the well data, reflecting the quality of the initial model. It also reveals lateral velocity variations and a good match with the sonic log (figure 2b), demonstrating the additional information provided by FWI. The velocity model building flow was completed by a calibrated tomographic update with the aim of preserving gathers flatness and ensuring a precise tie with the depth markers. The updated velocity model improves the imaging of faults within and above the anticline and produces flatter Common Image Gathers (CIGs) (figure 2c). This velocity model not only enhances imaging through migration but also

better constrains the deterministic inversion. Because the recorded dataset includes a 8 Hz low-cut acquisition filter, the seismic data lacks low-frequency information. This is typically compensated for by incorporating well data during deterministic inversion. In our case, the refined velocity model—while maintaining a good match to well data at their locations—was used in combination with the angle-stacked seismic data as input to the inversion workflow.

Stratigraphic elastic inversion

Thanks to the improved pre-processing and velocity model building, the final image is significantly enhanced compared to the legacy dataset. The unconformity present at the target level is clearly revealed and will help better define the reservoir boundary. The fault network located above and within the reservoir interval is more clearly imaged, improving the understanding of the reservoir compartmentalization. The presence of karst features has been identified, which is particularly important for well placement to avoid mud-loss issues. In addition to these imaging improvements, the main advantage of this reprocessing is the enhanced preservation and clarity of the AVA information. As described above, this was

particularly challenging due to multiple energy interfering with single reflection events, requiring accurate multiple attenuation at each sample of the dataset. The elastic attributes (I_p and V_p/V_s), inverted from the newly reprocessed four angle stacks (from 0 to 36 degrees), were used to identify fluid and lithology variations. A strong imprint of seismic noise and multiples on the P-impedance results was still visible in the legacy acoustic inversion, but this has been greatly reduced in the newly inverted attributes (figure 4 c & d). The V_p/V_s depth slices enable better discrimination and delineation of the hydrocarbon fluid contact compared to the I_p attribute (figure 4 e & f). This highlights the need to go beyond acoustic inversion to optimize future well placement. The cross-plot analysis reveals that low I_p combined with low V_p/V_s was a direct indication of the presence of hydrocarbons. Deterministic classification in the elastic domain was then applied to differentiate hydrocarbons from water-saturated carbonates, resulting in a good match with well data and a clear delineation of the oil contact (figure 3).

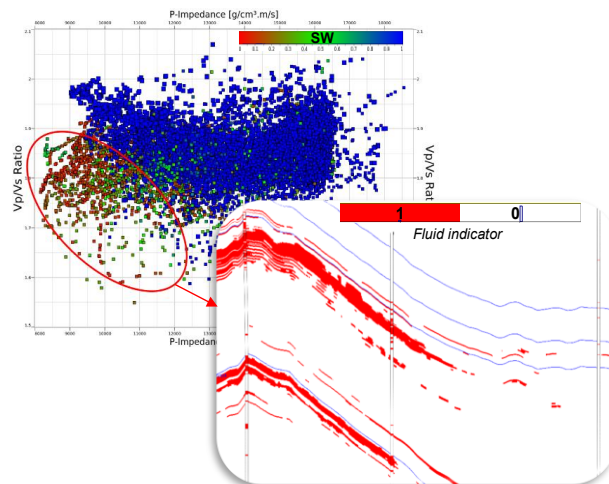


Figure 3: I_p - V_p/V_s crossplots from well logs color coded by water saturation. Selection is applied on inverted elastic attributes to obtain fluid indicator 1 for hydrocarbon and 0 for water saturated carbonate (bottom right picture)

Conclusion

The combination of shallow water and complex layer-cake geology makes the subsurface of the Arabian Gulf particularly challenging for imaging and reservoir characterization. The application of the latest seismic imaging technologies, including iterative demultiple processing constrained by well data, not only enabled the removal of multiples from the final image but also recovered reliable AVA information. In addition to advanced pre-processing, 15 Hz FWI was performed to obtain an accurate seismic image that properly honors well information and compensates for the lack of low-frequency content in the recorded seismic data, information that is crucial to get accurate stratigraphic seismic inversion results. Finally, the elastic attributes derived from our deterministic inversion enabled us to clearly delineate the hydrocarbon fluid contact, facilitating the future development of this oil field. This study highlights the benefits of integrating seismic imaging and reservoir inversion within a unified workflow. This integrated approach maximizes the information extracted from seismic data and enhances the reliability of hydrocarbon reservoir prediction while reducing the risk associated with drilling dry wells.

Acknowledgement

We thank QatarEnergy for permission to publish and for the fruitful collaboration during the entire reprocessing and inversion project.

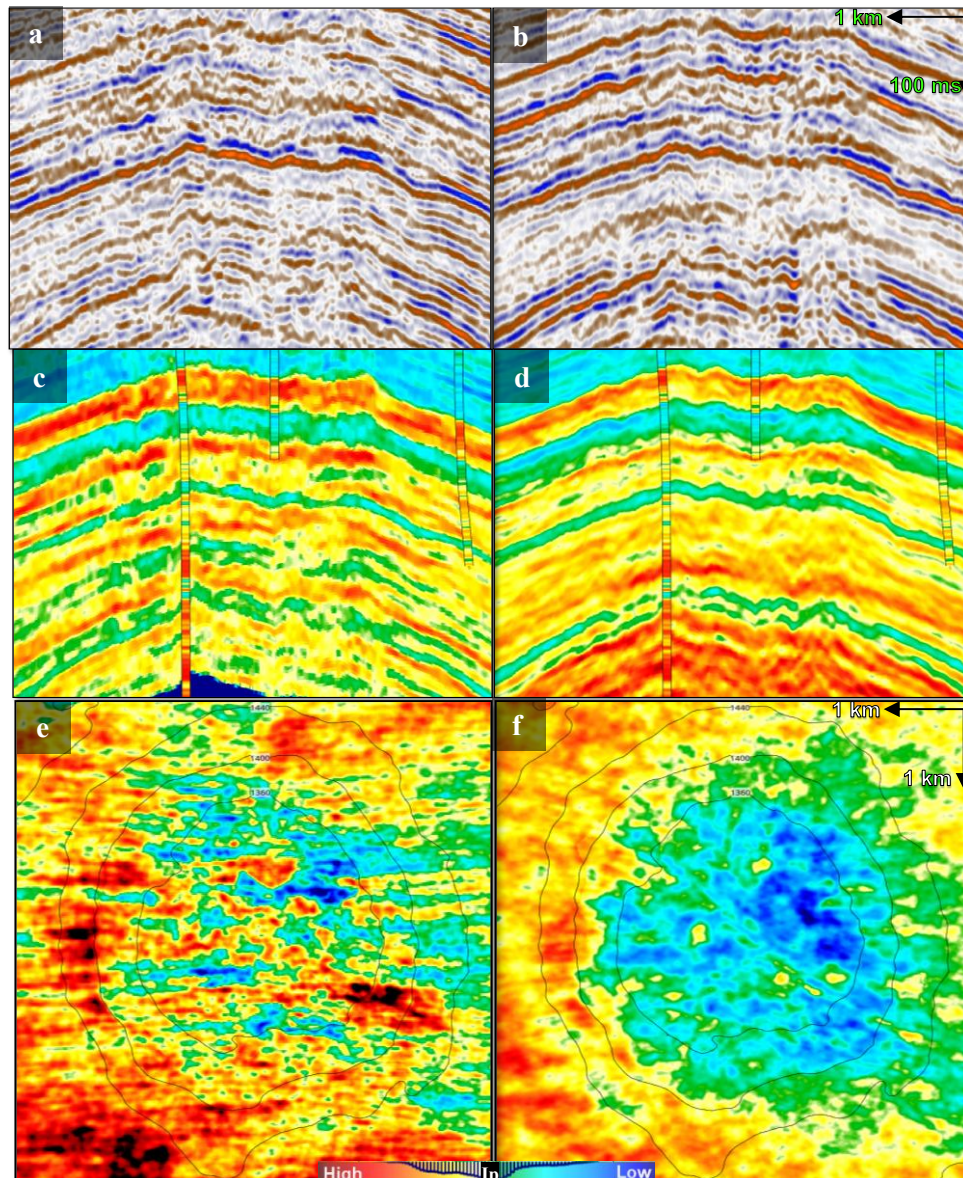


Figure 4: Comparison between legacy seismic and inverted P-Impedance (a & c) with reprocessing results (b & d). P-Impedance map slices for legacy (e) and reprocessing (f) are extracted at reservoir level.

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