Imaging Uplift Beneath Complex Near-Surface Overburden Using Q-based Imaging Workflow

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Summary

Seismic imaging beneath complex near-surface conditions remains a major challenge in marine settings, particularly in the Romanian Black Sea where Quaternary paleo-Danube submarine channels and shallow gas cause strong attenuation, velocity distortions, and loss of resolution. In the Ana–Doina–Bianca (ADB) area of the XV Midia Shallow Block, these effects have resulted in amplitude dimming, structural pull-down, and poor illumination of prospective targets.

This study presents results from a 2024-2025 3D seismic reprocessing project covering approximately 577 km² of legacy marine streamer data. The objective was to significantly improve image quality by explicitly addressing attenuation through Q-compensated Kirchhoff Prestack Depth Migration (Q-KPSDM), supported by an integrated earth model incorporating velocity, anisotropy, and absorption (Q). The workflow combined modern data conditioning, Full Waveform Inversion (FWI), reflection tomography, well calibration, and iterative, data-driven Q model updates.

The final anisotropic TTI Q-KPSDM volume shows clear imaging uplift beneath the Danube channel system, with improved bandwidth, reflector continuity, and structural accuracy compared with legacy processing. These improvements enhance reservoir interpretability and reduce subsurface uncertainty, supporting more reliable geological interpretation and development planning in the ADB area.

Introduction

The Ana and Doina gas fields are located within the Ana-Doina-Bianca (ADB) area of the XV Midia Shallow Block in the Romanian Black Sea. These fields produce dry biogenic gas from Late Miocene to Dacian shallow-marine sandstones at depths of approximately 1100 m. Despite the relatively modest burial depth of the reservoirs, seismic imaging in the area has long been recognized as problematic due to the presence of a highly heterogeneous near-surface overburden dominated by Quaternary paleo-Danube submarine channels and shallow gas accumulations.

Figure 1 shows the location of the Midia Block and the extent of the 2024 ADB reprocessing area, together with the mapped network of paleo-Danube channels at the seabed. The spatial correlation between the channel system and the areas of historically poor imaging underscores the importance of near-surface effects in this setting.

The Danube channel system is characterized by erosional features, infilled with unconsolidated sediments and locally charged with shallow gas. These elements generate strong lateral velocity variations, very low near-surface velocities, and pronounced seismic attenuation. The combined effect is frequency-dependent amplitude loss, phase dispersion, and kinematic distortion of deeper reflectors. In early seismic interpretations, these effects manifested as sagged structures and dimmed reservoir reflectors beneath the channel fairways, complicating both structural mapping and amplitude-based analyses (Duley and Fogg, 2009).

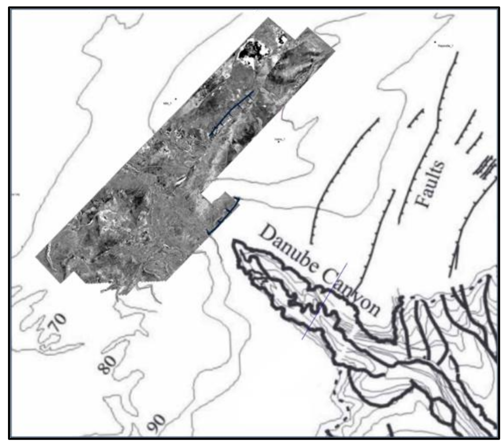

Figure 1 Map of the Midia Block, showing the 2024 ADB re-processing area and the network of paleo-Danube channels on the seabed.

Over the past decade, several generations of seismic processing and imaging have attempted to mitigate these challenges. A major benchmark reprocessing effort between 2016 and 2018 integrated Full Waveform Inversion (FWI) and early forms of Q compensation, leading to notable improvements in velocity model accuracy and overall image quality (Costriiciuc *et al*., 2018). Nevertheless, even these advanced workflows continued to struggle beneath the largest Danube channel segments, where residual attenuation and velocity errors persisted.

The 2024-2025 reprocessing project was therefore initiated with the explicit aim of addressing these remaining limitations. Building on industry advances in attenuation handling and depth imaging (e.g., Matta *et al*., 2021), the project focused on delivering a high-fidelity depth-migrated volume that robustly compensates for absorption while preserving true relative amplitudes. Particular emphasis was placed on imaging uplift beneath the Danube channel system, where improved seismic clarity has a direct impact on reservoir interpretation, development planning, and risk reduction.

Project Overview and Objectives

The dataset addressed in this study is a 3D single hydrophone streamer marine survey covering approximately 577 km² in the Block XV area offshore Romania. The data were acquired between December 2013 and January 2014 using a conventional tow configuration. Water depths across the survey range from roughly 30 to 80 m, resulting in strong short-period water-bottom multiples and peg-leg reverberations that further complicate the seismic response.

Legacy processing sequences included Prestack Time Migration (PreSTM) and earlier generations of Prestack Depth Migration (PSDM) and Q-PSDM. While these approaches provided incremental improvements, they consistently highlighted several key limitations:

- Persistent amplitude dimming and bandwidth loss beneath the Danube channel and shallow gas zones.
- Structural pull-down effects leading to uncertainty in depth positioning of reservoir horizons.
- Reduced event continuity and poor fault definition in channel-shadowed areas.
- Limited reliability of amplitude attributes for reservoir characterization.

The 2024–2025 reprocessing project was designed to overcome these limitations through a fully integrated depth-imaging workflow. The principal technical objectives were to:

- Improve spatial resolution, reflector continuity, and structural positioning throughout the stratigraphic section, with particular focus on channel-shadowed and gas-affected zones.
- Broaden the usable seismic bandwidth to enhance stratigraphic detail and wavelet stability at reservoir level.
- Build a high-fidelity anisotropic depth model incorporating velocity, anisotropy, and absorption (Q) that accurately captures near-surface and deeper subsurface heterogeneity.
- Mitigate the combined effects of shallow channels, gas pockets, and multiples on both kinematics and amplitudes.

From an operational perspective, the project also aimed to ensure robustness and consistency through continuous quality control. Interim migrated volumes were generated at multiple stages of the workflow and systematically compared with legacy images to verify that each processing and model-building step delivered tangible improvements.

Q-based Imaging Workflow

Effective depth imaging beneath complex near-surface conditions relies on robust early-stage data conditioning. In the ADB reprocessing, noise attenuation and bandwidth recovery were prioritised to preserve both kinematic fidelity and relative amplitudes before model building and migration.

Swell-noise attenuation was applied to suppress low-frequency contamination typical of shallow-water acquisition. Source and receiver deghosting were a key early step, recovering missing low- and high-frequency energy and improving wavelet stability – an essential foundation for FWI updates and reliable Q-estimation. Particular care was taken to preserve true relative amplitudes during this conditioning phase.

Given the shallow water depth, multiple attenuation remained a major challenge. A combined 3D SRME and SWIM sequence was used to tackle short-period reverberations and more complex peg-leg multiples. QC migrations throughout this phase confirmed improved signal-to-noise ratio, better bandwidth balance and more stable event continuity.

Velocity model building formed the core of the workflow. The starting model, based on legacy PSDM and well data, was refined using diving-wave FWI to depths of ~600 m (up to 12 Hz), resolving low-velocity channel infill and reducing early kinematic distortions. Below the diving-wave limit, several cycles of reflection tomography interleaved with reflection FWI improved medium-wavelength velocity structure and reflector focusing at reservoir level.

Well ties, checkshots and formation markers provided constraints on vertical velocities and anisotropy. A TTI model was adopted, with δ and ε adjusted to minimise misties and better position key horizons. Although the anisotropy model shows good agreement with well control, additional geological refinement remains a potential area for improvement.

A data-driven Q model was developed in parallel. A moderate background Q was combined with locally reduced values within shallow channel and gas-affected zones, guided by spectral attenuation analysis and sensitivity tests. Q updates were applied after each major FWI stage, and the evolving model was validated through comparisons of migrations with and without Q-compensation to avoid over-correction.

Final imaging used anisotropic TTI Q-KPSDM, integrating the refined velocity, anisotropy and Q models. Iterative PSDM updates continued until improvements became marginal, yielding a depth volume with more reliable representation of both shallow and deeper structures and improved handling of attenuation associated with the Danube channel system.

Results

The reprocessing delivers a clear uplift in seismic image quality across the ADB area, particularly beneath the paleo-Danube channel and shallow-gas zones. In the legacy image, reflectors beneath the channel appear dimmed and defocused, while the reprocessed Q-KPSDM section shows improved continuity and more stable phase behaviour (Figure 2a–b). The accompanying velocity/Q model (Figure 2c) highlights the shallow low-velocity, high-attenuation zone responsible for much of the original imaging distortion. Together, these updates reduce channel-related pull-down and provide a more reliable structural representation, although some residual effects remain where near-surface heterogeneity is strongest. These improvements help to stabilize both the imaging of deeper targets and the consistency of structural ties across the survey.

From a reservoir interpretation perspective, the improvement is well expressed in the producing field examples. Vertical sections through Wells 1 and 2 (Figure 3a–b) show that amplitude behaviour across the interpreted GWC becomes more stable after reprocessing, supporting more confident horizon mapping through channel affected areas. Attribute level QC reinforces this observation: the legacy impedance map shows only partial contact alignment, whereas the reprocessed map exhibits a more coherent anomaly that better follows the expected fluid contact between the wells (Figure 3c–d). Although some zones still show ambiguous conformance, these tend to coincide with areas where shallow complexity or geological variability remains difficult to model, and their extent is reduced compared with the legacy product.

Overall, the updated imaging and attribute response provide a more consistent foundation for structural interpretation and reservoir evaluation. The combined improvements in reflector continuity, contact behaviour and structural positioning result in a depth volume that supports more dependable mapping, depth correlation and amplitude-based analysis than the legacy data. While limitations persist due to strong shallow attenuation and velocity variability, the reprocessed Q-KPSDM volume enables a clearer assessment of reservoir geometry and associated uncertainties.

Further enhancements could be achieved by extending FWI to higher frequencies to better resolve fine-scale shallow heterogeneity. Additional refinement of the anisotropy model, guided by geological inputs, and continued development of joint velocity–Q inversion approaches may further improve amplitude fidelity. Future reprocessing or new acquisition with wider azimuths and longer offsets would also benefit imaging in areas affected by shallow gas.

Conclusions

This study demonstrates that significant imaging uplift can be achieved in challenging absorption and dispersion environments through the careful integration of modern data conditioning, high-resolution velocity model building, and explicit attenuation compensation in depth imaging. By combining advanced noise and multiple attenuation with an FWI-driven velocity and anisotropy workflow, supported by a data-driven Q model, the reprocessing successfully mitigates the combined effects of near-surface heterogeneity, shallow gas, and absorption on seismic amplitudes and kinematics.

The final anisotropic Q-compensated Prestack Depth Migration volume shows marked improvements in bandwidth, reflector continuity, and structural accuracy when compared with legacy imaging. Previously obscured or distorted events are recovered with more stable phase behavior and improved depth positioning, leading to enhanced interpretability at reservoir level. Importantly, the restored relative amplitudes provide a more reliable basis for quantitative interpretation, including amplitude-based analyses and reservoir characterization.

Although the workflow did not rely on full 3D Q-tomography, the iterative, pragmatically constrained Q model proved sufficient to capture the dominant attenuation effects and deliver a robust uplift in image quality. The results highlight the value of integrating attenuation handling directly into depth imaging workflows, rather than treating it as a secondary or cosmetic correction. Overall, the approach outlined here illustrates how legacy marine seismic data can be transformed into a high-fidelity depth image, reducing subsurface uncertainty and supporting more confident geological and development decisions in complex near-surface settings.

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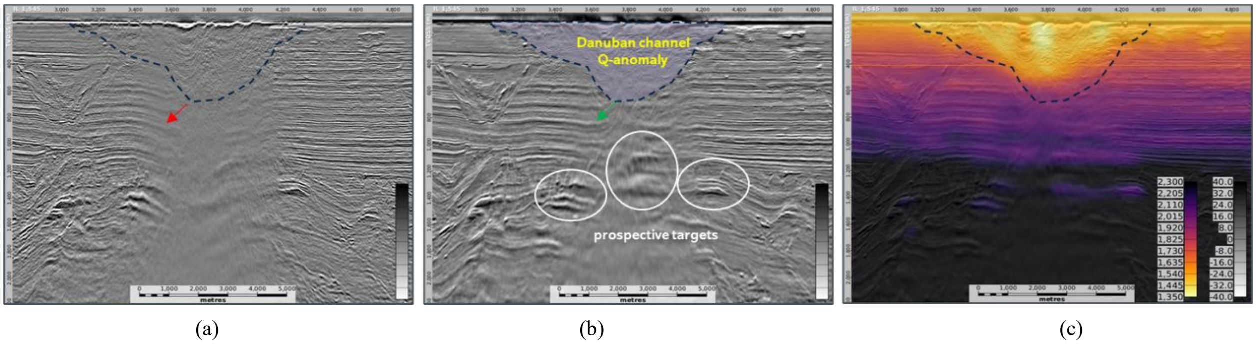

Figure 2: Comparison between legacy and reprocessed imaging results; (a) legacy Q-KPSDM section showing amplitude dimming, wavelet dispersion and reduced continuity beneath the paleo-Danube channel, (b) reprocessed Q-KPSDM section displaying improved reflector continuity and bandwidth, with reduced pull-down beneath the channelized overburden, (c) corresponding velocity model showing the shallow low-velocity zone where a locally reduced Q value was applied to capture the dominant attenuation effects beneath the paleo-Danube channel

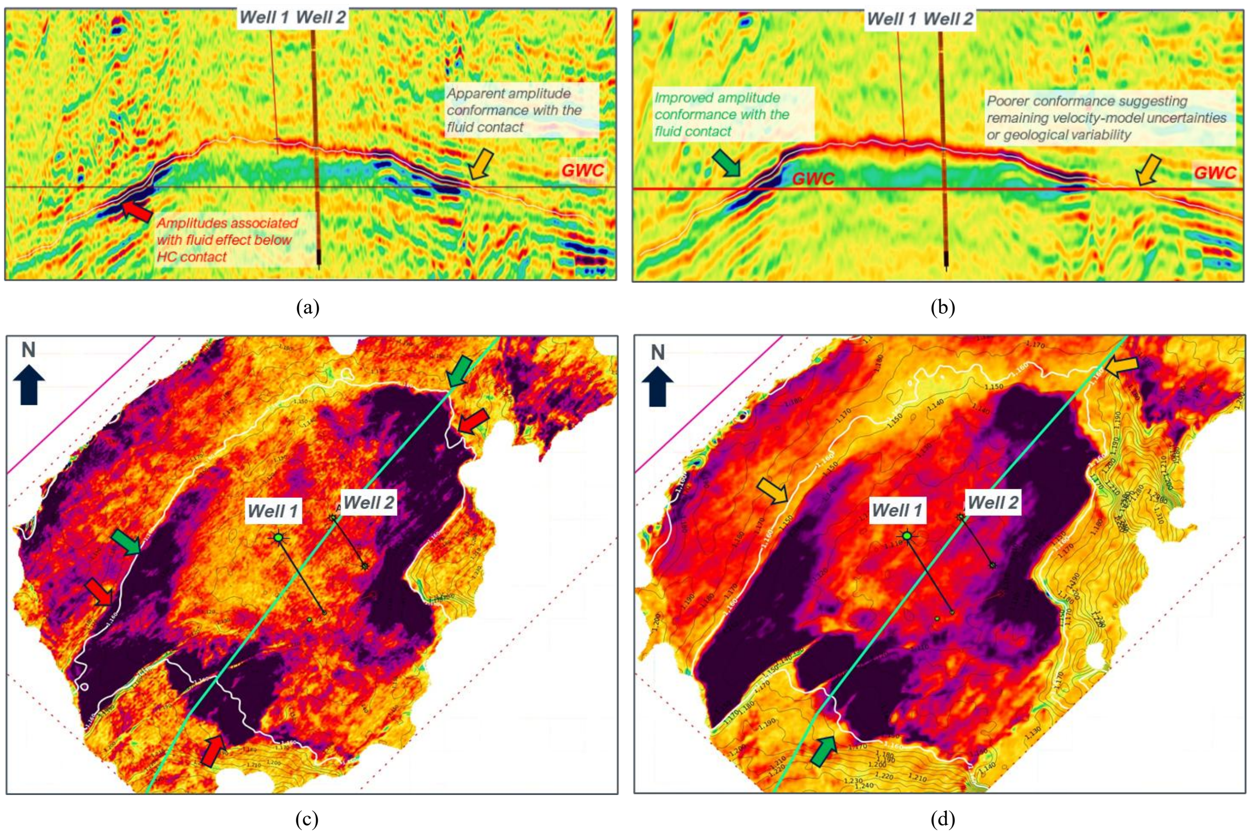

Figure 3: Prospect-scale QC panels from the producing field area (legacy vs reprocessed Q-KPSDM); (a) legacy vertical section showing inconsistent amplitude behaviour around the interpreted gas-water contact (GWC). Red arrows highlight areas where amplitude conformance is ambiguous due to residual near-surface effects, (b) reprocessed Q-KPSDM section showing improved reflector continuity and more stable amplitude alignment with the GWC, (c) legacy relative acoustic impedance map. The impedance anomaly shows inconsistent alignment with the interpreted fluid contact. Red arrows highlight places where the anomaly does not follow the expected contact geometry. These are areas where the seismic response is likely affected by near-surface, (d) reprocessed Q-KPSDM impedance map. The impedance anomaly displays clearer and more continuous conformance to the interpreted fluid contact. Green arrows mark locations where the anomaly matches the contact more convincingly, providing stronger support for mapping the fluid boundary. Orange arrows highlight areas where the relationship between the anomaly and the contact is still uncertain or open to interpretation, reflecting remaining model or geological complexity.