Innovative Depth Imaging and Broadband Processing: A case study from Erha 4D Broadband Reprocessing Project

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ABSTRACT

3D Seismic data over Erha Field is characterized with artefacts arising from overburden effects of shallow channels. The resultant effects are imaging challenges (sags) and seismic amplitude washouts down to reservoir targets. In this paper, we present a case study wherein we re-processed the Erha monitor 2 (M2) broadband acquisition which was previously co-processed with the Monitor 1 (M1) targeting the 4D difference only, as this initial processing did not take full advantage of the broadband acquisition. In order to improve the sub-optimal velocity model associated with the shallow gas zones, we utilized an integrated processing solution that consisted of broadband processing, integrated de-multiple workflows, Full wave Inversion velocity model building (FWI-VMB), Q-model building and pre-stack depth migration. Our innovative approach in this re-processing has significantly improved the imaging of the reservoir targets, increased Signal-to-Noise Ratio (SNR), leading to better stratigraphic imaging and amplitude strength. The prominent structural sags were corrected by the FWI Velocity Model, washouts corrected by Q model, using Q-migration engine. This reprocessing effort has provided higher data confidence and reduced the depth structural uncertainties associated with opportunities under the shallow gas anomaly.

Keywords: Full Wave Inversion, Amplitude, Signal-to-Noise Ratio (SNR), Broadband, Processing, De-Ghosting, Velocity model, De-Multiple

INTRODUCTION

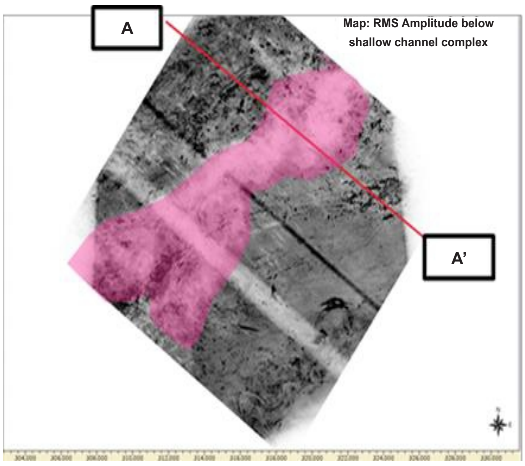
The Erha Field is a deepwater asset (water depth ranging 800m-1800m), located in OML 133, approximately 100km offshore western Niger Delta Basin (Figure 1). In Erha, the younger channels in the overburden are often charged with gas especially, a large channel complex just below the seafloor which traverses the center of the field from northeast to southwest (Figure 2). These complex shallow gas anomalies cause significant signal attenuation and multiple noise bouncing between gas-bearing thin layers (Gudipati *et al.,* 2018).

The shallow channel complex strongly attenuates seismic signals below it, including portions of Erha Main and significant parts of Erha North (see Figure 3). Attenuation appears primarily due to gas accumulation in the shallow channel, but strong diffracted multiples also suggest a scattering attenuation component. These issues, compounded by weak reflectivity and low signal-to-noise ratio (S/N) in the gas effect attenuation area, cascaded into sub-optimal amplitude and phase fidelity at the reservoir, poor well-ties between geologic markers and seismic events and poor imaging. The interplay of complex structural and stratigraphic complexity in Erha results in poor resolution and prediction of lithofacies. This increased subsurface uncertainty posed a higher risk in well placement and makes optimum field development more challenging. Obscured portions of the reservoir image impact gross rock volume (GRV) estimates, and suppressed amplitudes impact the calibration of reservoir properties, both of which are key inputs to the reservoir characterization.

Figure 1: Acreages with ExxonMobil interest in the Niger Delta Basin showing study location

The authors wish to thank the Nigerian National Petroleum Corporation (NNPC), Esso Exploration and Production Nigeria Limited (EEPNL), and Shell Nigeria Exploration and Production Company (SNEPCO) for the release of the materials and permission to publish this work. Many thanks to the Geoscience community of the EEPNL for technical reviews and suggestions.

NAPE Bulletin, V.31 No 1 (April 2022) P. 10-18



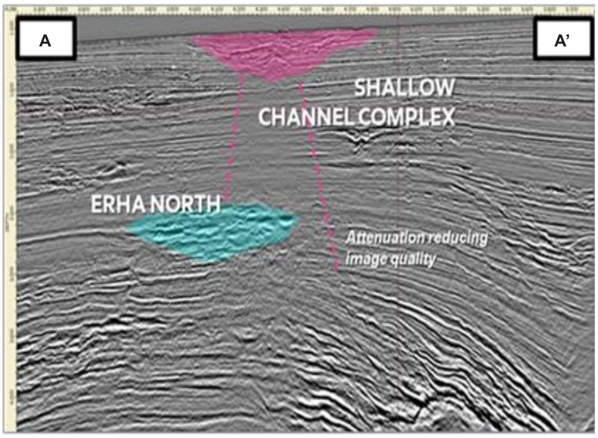


Figure 2: Shallow channel position shown in RMS amplitude extraction map-view (left) and section-view (right). Strong attenuation covering a significant part of the field leading to complex issues is shown.

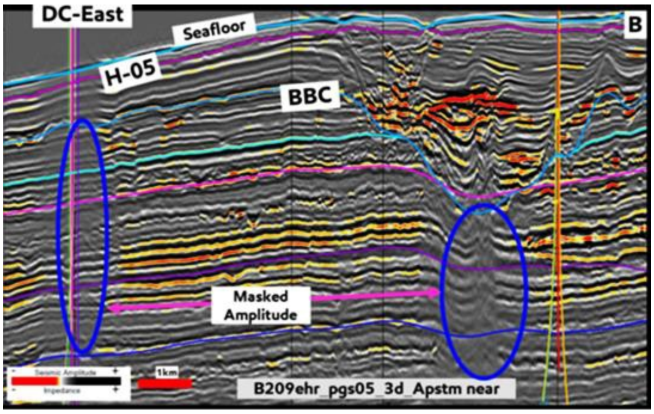


Figure 3: Shows Erha multiple geological challenges (Washout zones, Sags, poor reflection continuity and poor resolution).

In order to enable the effective development of the Erha Field, and to further improve the seismic imaging and the lateral events and fault positioning to de-risk some new drilling opportunities identified in the conventional M1 data, EPNL acquired a 3D high resolution Erha Monitor 2 (M2) Broadband acquisition in 2014 which was previously co-processed with the Monitor 1 (M1) targeting the 4D difference only for field development purpose. However, since 4D processing requires the comparison datasets to be as similar as possible, the full bandwidth of the M2 data could not be used at that time (governed by the lower M1 data bandwidth).

In order to fully realize the inherent frequency potential of the 4D M2 Broadband dataset, a reprocessing effort was carried out in 2019 aimed at addressing the multifaceted complex imaging problems inherent in the data. A two-pronged approach was adopted for the 2019 re-processing which include work efforts performed by both the processing vendor (e.g. De-multiple, De-ghost, Migration, Post-processing) and in-house (e.g. Q-model building, FWI –VMB workflows).

In this paper, we present the key innovative broadband processing steps used to significantly optimize seismic bandwidth for improved definition of reservoir architecture and compartmentalization. We also demonstrate the integrated signal processing, FWI velocity model and Q-model building used to develop high-resolution velocity and attenuation models to alleviate shallow gas effects masking the imaging of the target reservoirs. An important aspect of the work is the near-real-time seismic interpretation feedback from the collaboration with the in-house interpreters during the FWI-VMB constrained by wells and interpreted surfaces which is very key to modelling and resolving the complex imaging and overburden challenges.

Geologic Framework

The Niger Delta basin is primarily a linked extensional - compressional tectonic system with distinct structural provinces (Corredor *et al.,* 2005) (Figure 4a). Updip, extension at the shelf margin is composed of landward dipping growth faults and basinward dipping normal faults. The field is set-up by a large regional detachment fold which is positioned in the boundary between a coupled extensional–contractional systems (see Figure 4b). Downdip and along slope, is dominantly compressional and composed of large mobile shale cored folds, followed by smaller scale buckle folds and finally ends in belts of low relief toe-thrusts. This system is driven by gravitational collapse of a prograding deltaic sediment wedge that prograded along with the sediment wedge (Corredor *et al.,* 2005; Obi *et al.,* 2018).

Early development drilling demonstrated the presence of locally sealing shales especially at the deeper intervals. The structure of the field is gently dipping shale cored

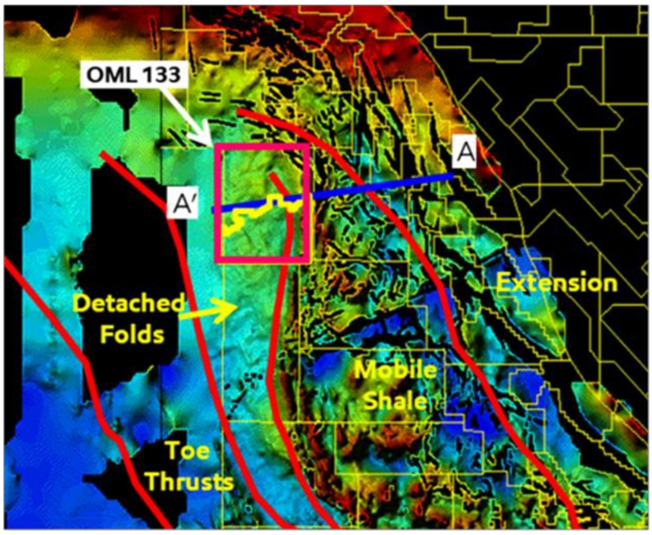


Figure 4a: Regional Depth Map of Top of Oligocene showing Tectonic setting of OML 133.

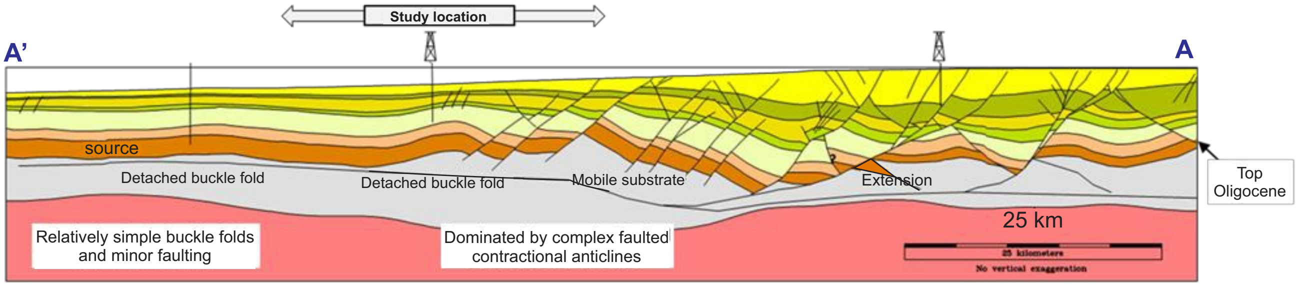


Figure 4b: Sub-regional transect showing structural provinces (coupled extensional – compressional system). Study location sits on a detachment fold in central portion of asset (Courtesy ExxonMobil Deepwater Collaborative 1999).

faulted anticline, setup by a large regional detachment fault with series of east and west dipping faults that compartmentalizes the field into fault blocks. The reservoir consists of four stacked Upper Miocene Deepwater channel complex (CCS) systems. The complex stratigraphic and structural features lead to severe compartmentalization of the reservoirs (see Figure 5).

METHODOLOGY AND DISCUSSION OF RESULTS

The two major components of the re-processing effort were executed in parallel, The Processing vendor carried out the broadband time processing which includes high effort De-noise, De-multiple, De-ghosting etc. while ExxonMobil's Upstream Integrated Solutions (UIS) carried out the state-of-the-art Q (attenuation) and FWI velocity model building (QVMB) (see Figure 6). Recent experiences have demonstrated the value of an integrated model building approach where geologic concepts, interpretation, and well-data inputs can be incorporated into traditional seismic VMB and FWI workflows. Carrying out the QVMB work in house eradicates the communication and access barriers between the processors and interpreters.

Specifically, the scope of QVMB includes building a regional and high-resolution tilted transverse isotropy (TTI) model suite, including velocity and anisotropy models, from surface seismic and well data and building a high-resolution attenuation (Q) model for the shallow gas bodies. Vintage data from 2011 time processing had been used in the QVMB process until cleaner 2019 intermediate time-processed data was made available by the in-country processing vendor. The final TTI model suite was delivered to Vendor for final Q Migration (QAPSDM).

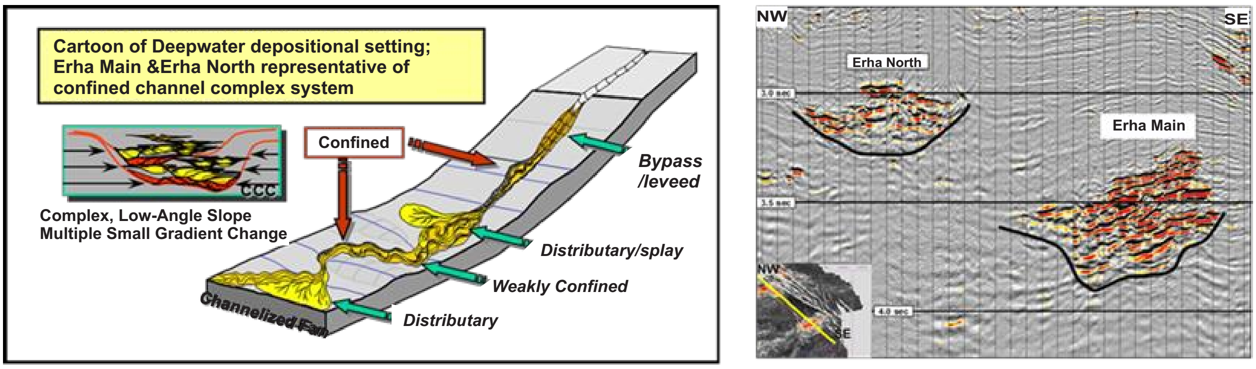


Figure 5: Deepwater depositional settings typical of Erha Fields. Erha Main and North reservoirs in a confined channel complex systems.

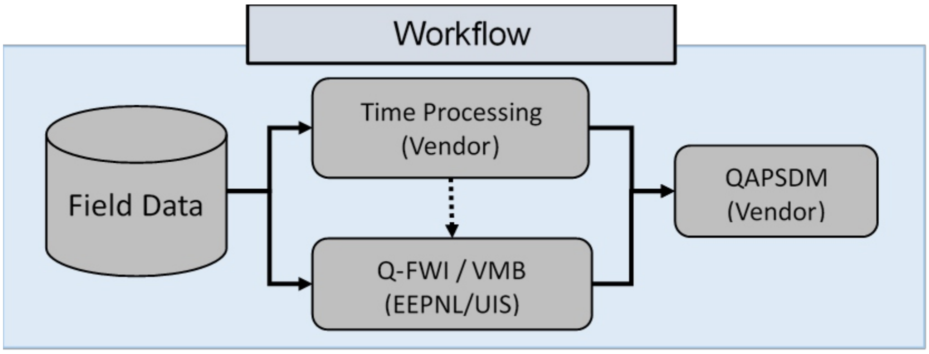


Figure 6: Overall workflow for the 2019 Erha Broadband Processing effort. Broadband processing and data pre-processing was carried out by in-country vendor, while FWI and QVMB was carried out in-house.

Broadband Processing – De-Ghosting

The broadband acquisition has expanded the useable low and high frequencies of the seismic signal. The increased receiver coverage allows for a more complete sampling of the total wavefield. Multicomponent sensor technology provides broadband acquisition and allows for separation of the downgoing and upgoing wavefields at the receivers. Several benefits are associated with 3D acquisition and processing of dual-sensor streamer data, including improved demultiple (Hegge *et al.,* 2011), an optimal platform for high-end velocity model building (Kelly *et al.,* 2010), and more robust reservoir characterization (Reiser, 2011).
De-ghosting aims to remove the effects of the source and receiver ghosts from the data. The receiver ghost had already been removed on board acquisition through the wavefield separation process; therefore, de-ghosting at this stage was targeted at removing the source ghost energy only. The source depth is 5m, and with a water velocity of 1540m/s, the source ghost period is 5.8ms with the first notch frequency at 155Hz. Spatially varying de-ghosting operators were derived and applied to common arrival angle planes to correct for the angle dependence of the ghost period. De-ghosting was effective at removing source ghost and successfully recovering the source notch (Figure 7).

Correctly de-ghosting the data has many benefits, such as recovery of information at the ghost notches, improvement in interpretability due to fewer side lobes in the wavelet, and increased confidence in amplitude variation with offset. In particular, the low-frequency boost of the de-ghosted data helped with providing reliable low-frequency information which is the ideal input to FWI –VMB. The expanded data bandwidth, characterized by the more compact source wavelet, also improved the multiple prediction model and multiple subtraction results. The effect of de-ghosting on the data is shown in Figure 8.

De-multiple

3D Surface-Related Multiple Elimination (3D SRME) was used to eliminate water-bottom related multiples in the data. The water depth in this survey was gently dipping between 770 m and 1329m which corresponds to water

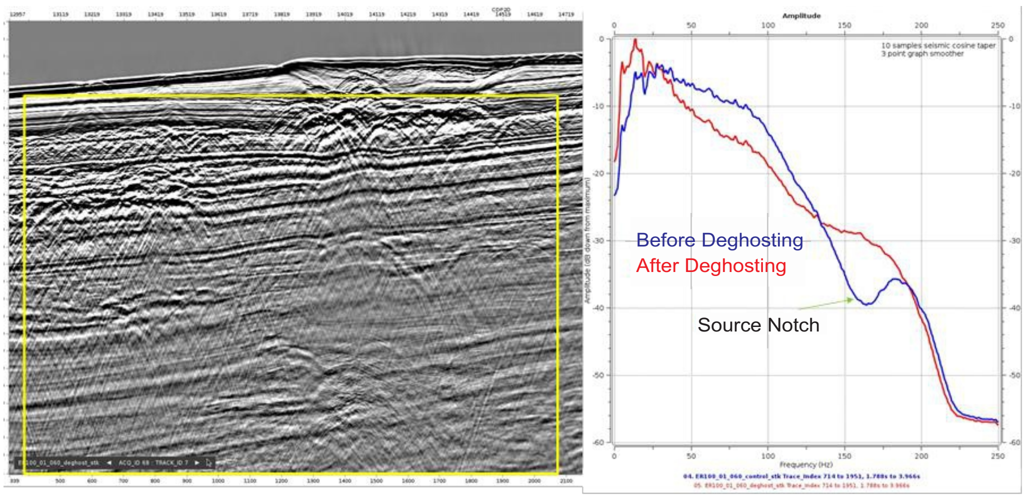


Figure 7: 2D stack before and after de-ghosting; Spectrum showing source ghost notch had been boosted.

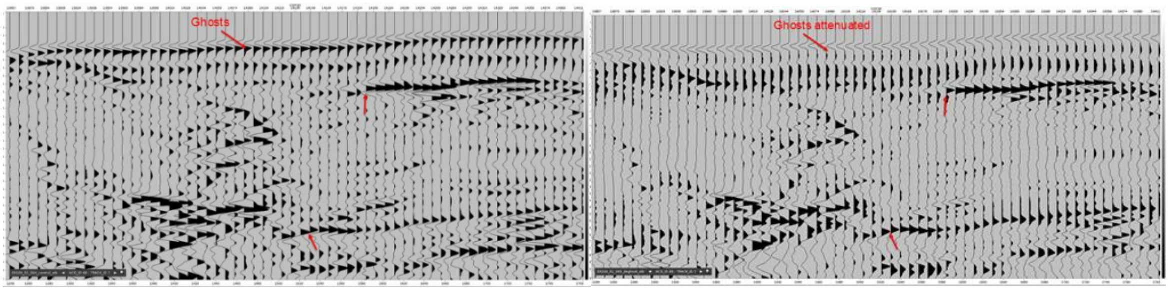


Figure 8: 2D stack before and after de-ghosting; Source side ghosts and side lobes had been significantly attenuated.

layer multiple periods of 3200ms (for 1540m/s water velocity). The vintage 2005 narrow azimuth (NAZ) data was merged with the multicomponent (M2) narrow azimuth data to build a high-fidelity multiple model to fill in missing near offsets in the undershoot area. Residual multiples were subsequently attenuated by HR Radon de-multiple. The cube was binned with data at the natural acquisition density: 6.25m XL spacing, 12.5m IL spacing, and 75 m offset spacing to create dense and more accurate multiple predictions.

The predicted models were globally matched independently and then multi-model subtraction of the two sets of predictions from (i) the narrow azimuth cube and (ii) the undershoot cube was performed using three frequency bands. Multi-model adaptive subtraction approach led to a better final multiple subtraction on the undershoot data (see Figure 9).

This method proved successful in attenuating surface related multiples hence improving the migrated image.

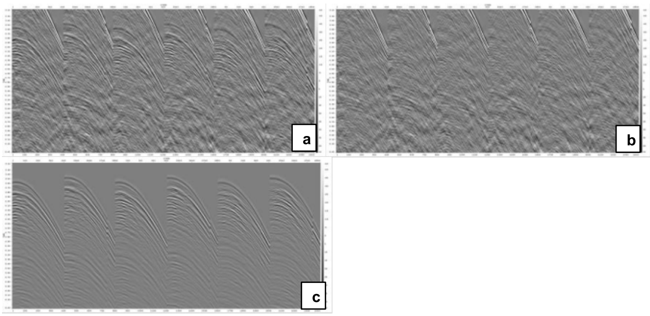


Figure 9: Shot gathers before (a) and after (b) SRME de-multiple; (c) is showing the difference plots.

A high-resolution Radon de-multiple was run in order to attenuate residual multiple present in the data that had considerable move-out differentiation from the primary reflectors below the first water bottom multiple bounce. Application of the Radon de-multiple was seen to effectively attenuate residual multiples and unwanted noise in deep areas from the data enhancing the input to migration (Figure 10).

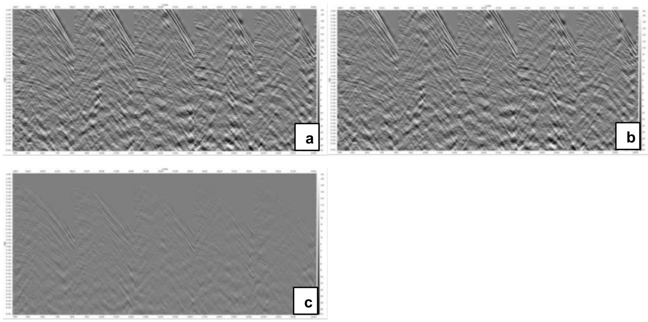


Figure 10: Shot gathers before (a) and after (b) residual de-multiple using HR-Radon; (c) is showing the difference plots.

Velocity Model Building (VMB)

Since the 2019 M2 broadband re-processing would not be constrained by 4D repeatability, it provided an opportunity to update the seismic velocity model. Recent success in applying FWI to Q-model building (for attenuation compensation) in analogous assets globally, suggested that the issues caused by the shallow channel complex at Erha could be significantly mitigated. However, the recent experience have demonstrated the value of an integrated model building approach where geologic concepts, interpretation, and well-data inputs can be incorporated into traditional seismic VMB and FWI workflows. This integrated approach works best where communication and access barriers between the processors and interpreters are minimized, so model-building was preferred to be carried out in-house.

The overall FWI/QVMB workflow was driven by four key technologies as follows:

· Integrated Model Building (IMB) technology- to manually update velocity and anisotropy models to fit checkshots, markers and flatten the gathers while honoring the geologic structures.
· Reflection tomography - to update the velocity model such that the curvatures in the migrated gathers are minimized.
· Diving-wave FWI - to obtain a high-resolution velocity model
· High-resolution Q model building - to compensate for the attenuation effect of shallow gas bodies.

Various geologic data including well data was imported and loaded into the IMB processing system, including well data and key interpreted geologic horizons to drive the process. Initial velocity and anisotropy model building provided a starting model for tomography and FWI. The starting model captured the regional trend of the geology.

Initial velocity and anisotropy parameter models was built from various data, including surface seismic, well data (e.g., sonic, gamma logs), check shots, vertical seismic profile, and interpreted geologic horizons. The checkshots data were used to construct the initial vertical velocity (Vp) at various well locations across the Erha Field. Vp profiles (Figure 11), were constructed to match the checkshots data at the well locations within 10ms uncertainty and were interpolated along the three regional horizons to fill in the whole Erha area.

Similarly, Delta and Epsilon models (Figure 11) were also constructed at the well locations to flatten the gathers especially at far offsets and were interpolated along the regional horizons to fill in the whole Erha area. Epsilon model was linked to Delta model by the following relationship to ensure that Delta was no greater than Epsilon:

Epsilon = {0.5*Delta, if Delta $\leq$ 0; 1.85*Delta, if Delta>0.}

This initial velocity model was then updated using reflection tomography down to the major horizons via a layer-stripping approach to minimize residual moveout, constrained by the check shots and well markers (see Figure 12). Once the initial velocity and anisotropic parameter models were created and deemed to be reasonable based on image gather flatness and fit to well data, they were used as the starting models for FWI to further update and improve the resolution of the velocity model (Ayeni *et al.,* 2017).

Full-wavefield inversion

There are numerous shallow gas bodies of various sizes in Erha area that necessitated a high-resolution velocity model to mitigate the distorted and de-focused image under the gas bodies. FWI was performed from low (3Hz) to high frequencies (9Hz) to resolve the shallow velocity features. The diving wave portion of the raw hydrophone data (H-RAW) was used as input data to FWI. The seismic data was spectrally shaped such that the data are zero-phased and have a flat spectrum. To achieve this, a match filter was designed between the estimated wavelet high cut at 15Hz and the target wavelet. The matching filter was then applied to the data. The H-RAW gathers before and after shaping are displayed in Figure 13.
FWI was sequentially run at 3Hz, 7Hz, 12Hz and 15Hz iteratively. For each frequency band, the corresponding

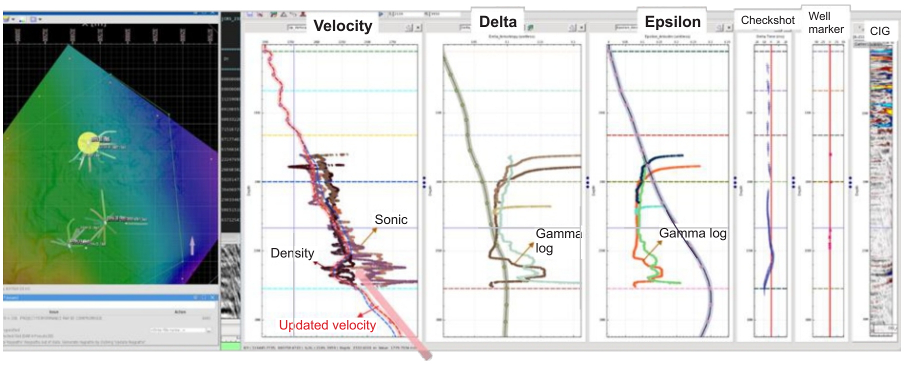


Figure 11: Vp profile (left-most panel) constructed to fit the checkshot data within 10ms; Delta profile (2nd panel) constructed to flatten the migrated gather; Epsilon profile (3rd panel) constructed to flatten the migrated gathers.

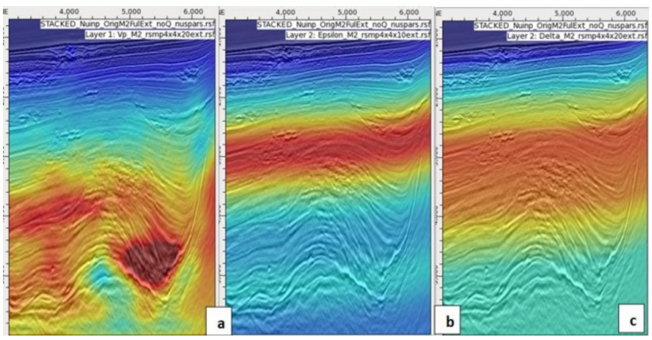


Figure 12: Stack overlain by (a) the updated final velocity, (b) the final updated epsilon model, (c) the final updated delta model.

bandpass filtering was applied. Tomography updates was run severally to optimize gather flatness. The FWI was able to capture the smaller, deeper gas pocket and improve the image focusing under the gas pockets resulting in a significant imaging improvements of the QAPSDM volume.
The resulting final velocity model was more consistent with geologic features (i.e., a smooth regional structural trend along with localized geologic anomalies. The improved vertical and lateral resolution of our velocity and anisotropy parameter models helps delineate geologically plausible images without abrupt structural disconformity (see Figure 14).
Well marker integration was performed after few post FWI

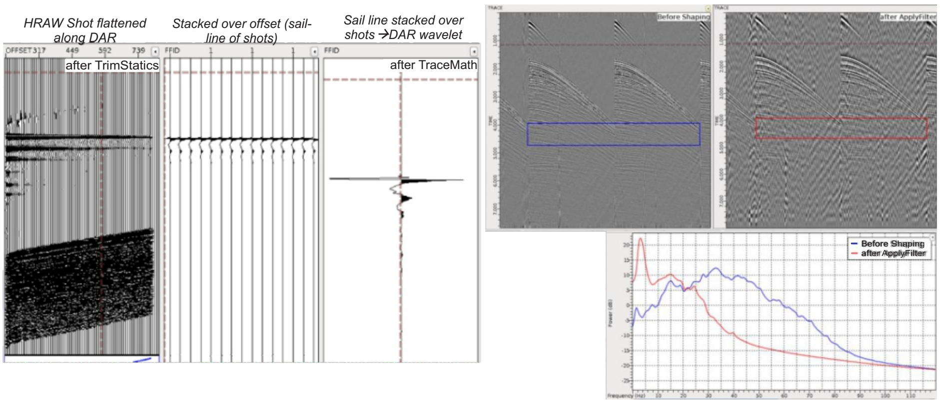


Figure 13: H-RAW Wavelet and Shaping. (a) Wavelet estimated from direct arrival (DAR) on H-RAW shots (b) Shots before and after shaping filter application.

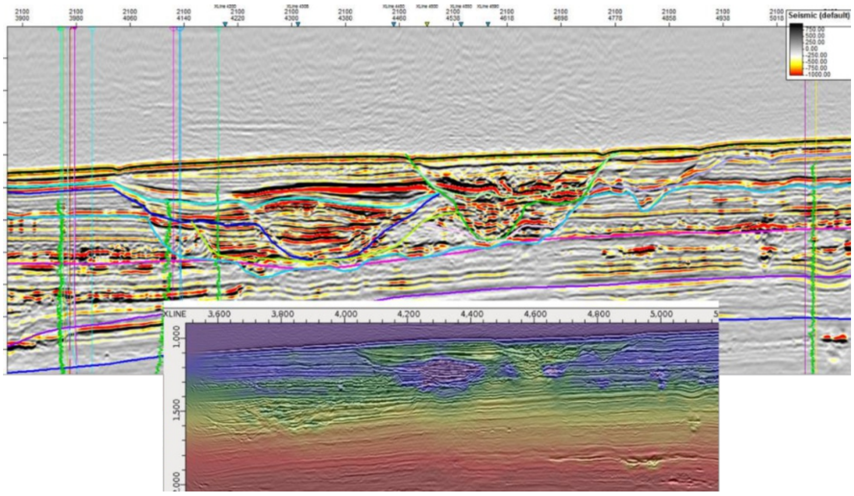


Figure 14: FWI velocity models captures the details of the channel patterns as pockets of velocity anomalies.

tomographic updates, the well marker mis-tie data, based on the new interpretation framework, was available, enabling further velocity and anisotropy update near the well locations. The updated models at the wells were extrapolated along geologic horizons, and smoothed with a larger scale up to 4km lateral and 100m vertical direction. The updated image was delivered to EEPNL interpreters for an updated marker mistie interpretation. The resulting new updated well marker mis-tie data were incorporated to finalize the model (see Figure 15).

High-resolution Q model building

Following an optimized velocity and anisotropic models, a high-resolution Q model was built to compensate for the attenuation loss and phase distortions caused by the shallow gas bodies. A shallow depth slice of the Q bodies is displayed in Figure 16. Thanks to FWI, all the shallow gas bodies had been detected as low velocity anomalies. The gas bodies were extracted and the Q values within the gas bodies were scanned such that the amplitude spectra

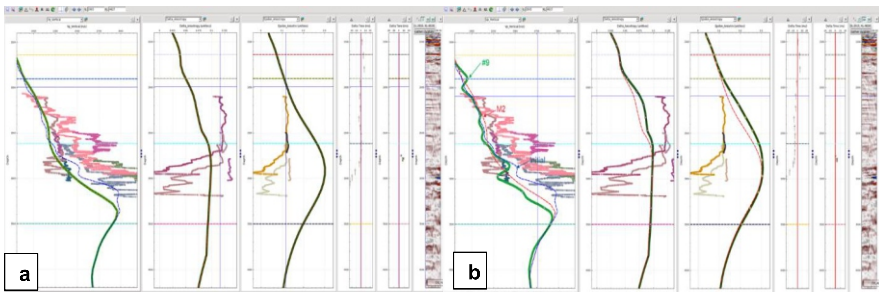


Figure 15: Well data analysis at Erha North. Each panel displays velocity vs. sonic curve, epsilon vs. gamma, delta vs. gamma, checkshot, markers and gather. (a) Before well marker misfit correction, (b) after well marker misfit correction.

were properly restored. Typically, estimating Q value is done in a seismic-amplitude-based approach, such as spectral ratio and centroid frequency shift methods (Tonn, 1991; Quan and Harris, 1993). However, in practice, the correct Q value estimation is difficult due to multiple factors:

1. Poor S/N due to strong seismic attenuation
2. Unreliable reference spectrum or wavelet selection
3. Spatial variation of frequency and amplitude content in the seismic image due to lithologic change and difference.

The rapid scenario testing of various Q models and imaging while in collaboration with the interpreters enabled us to resolve these challenges and develop the most geologically plausible Q model. Shallow Q models were built primarily for main channel complexes and some secondary Q geobodies were also built as necessary. The migration with and without local Q compensation at Erha Field is illustrated in Figure 17.

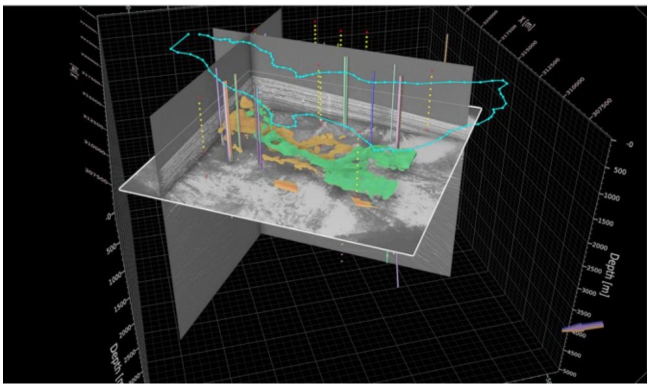


Figure 16: A shallow depth slice showing the outline of the identified Q bodies in Erha Field..

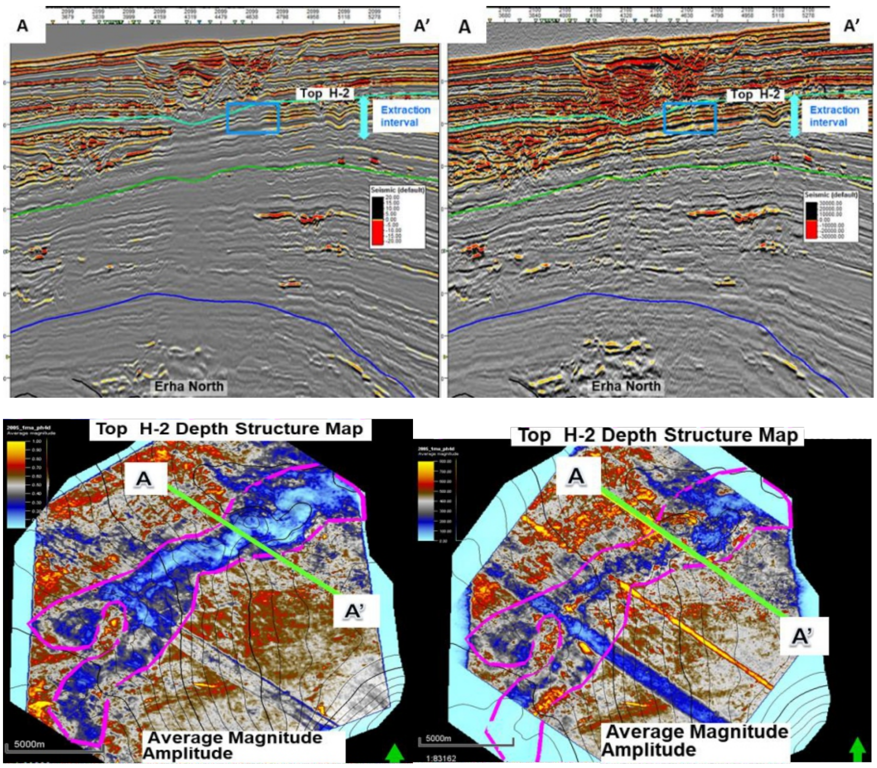


Figure 17. Maximum amplitude map extracted along the horizon (a) before and (b) after Q migration. (b) The new Q model helps properly restore seismic amplitude.

CONCLUSIONS

The innovative depth imaging and broadband processing workflows coupled with advanced velocity model building and de-multiple techniques integrated in the reprocessing efforts of the Erha M2 Broadband data has resulted in overall significant data improvement in terms of signal to noise ratio (SNR) and imaging. The shallow gas attenuation, velocity sags and the fault shadow issues were significantly mitigated by the FWI and Q-model combination leading to significantly improved imaging of fault plane with better reservoir characterization and STOIIP calculation. The high resolution broadband processing has resulted in better stratigraphic resolution, better discrimination of sedimentary facies, compartmentalization and enhanced shallow hazard identification. The boosted low frequencies in broadband data enhanced the derivation of more accurate seismic inversion products leading to better reservoir models and infill development plans. It is expected that the addition of this new reprocessed broadband seismic volume will lead to new opportunities as well as adjusted well placements for optimized production.

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