Role of Advanced Seismic Processing in De-risking Investment Decisions in a Poorly Imaged, Structurally Complex Usari Graben

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Usari field is a prolific oil and gas field, located offshore Niger Delta, It is the second largest field in the NNPC-MPN Joint Venture acreage operated by ExxonMobil. Usari field is set-up by two extensional faults with five reservoir groups, namely the Base Qua Iboe (BQI), Shallow, Intermediate, Deep and Graben reservoirs.

The Usari Graben, set up by opposed-dip faults is highly faulted, creating series of fault-dependent hydrocarbon traps. In addition to the highly faulted nature, a shallow gas cloud obscures ~70% of the Graben, and the combination negatively impacted seismic imaging and hence drill well opportunity identification. As a consequence, the Graben remained relatively undeveloped till date. Reprocessing the existing seismic data using Full Wavefield Inversion (FWI) technology became imperative in order to reduce these structural uncertainties and help with subsurface characterization.

The primary objective of the FWI processing was to produce earth models for improved imaging beneath the shallow gas anomalies and within fault-shadows regions. The FWI workflow is an integrated but flexible pre-migration seismic processing that enables simultaneous estimation of multiple subsurface parameters utilizing raw seismic data including refractions, diving waves, and wide-angle reflections. Overall, seismic imaging and reflection continuity improved due to better resolution and fidelity of velocity and anisotropy models in the vicinity of the fault-shadows, and below the shallow gas clouds reducing reflector sags. Also, weak amplitudes in deep sections were enhanced by careful application of attenuation compensation.

This study highlights the impact of the FWI processing from an interpreter's perspective on subsurface reservoir characterization with respect to reservoir connectivity, resource estimation, well placement, and understanding production behavior. In this paper, we present information deduced from the FWI seismic that was not imaged on conventional processed seismic dataset and which re-iterate the immense value of FWI processing in proper reservoir characterization and its impact on re-development investment decisions.

Key Words

Full Wavefield Inversion (FWI), Pre-Stack Depth Migration (PSDM), Pre-Stack Time Migration (PSTM), Joint Venture (JV), Ocean Bottom Cable (OBC), Shallow Gas, Usari.

1.0 Introduction

1.1 Usari Image Problem

The Usari Graben is characterized as a poorly or inadequately imaged zone mainly because of the incoherent seismic stacks in the previously available Pre-Stack Time Migration (PSTM) seismic data. The Graben, set up by opposed-dip faults is highly faulted, and in addition to the complex faulting, a shallow gas cloud obscures ~70% of the area (Figure 1). This combination negatively impacted seismic imaging and hence drill well opportunity identification. Other imaging issues includes reflector sags, non-geologic undulations/kinks caused by the complexly varying velocities within the graben and in the vicinity of faults (Fault shadows/near-fault sags) and image degradations as observed on the existing PSTM processed seismic. This has been discussed by previous authors (Reilly et al 1998, Aikulola et al., 2010). As a consequence, the Graben remained relatively undeveloped till date. Reprocessing the existing seismic data using FWI became imperative in order to reduce these structural uncertainties and help with subsurface characterization.

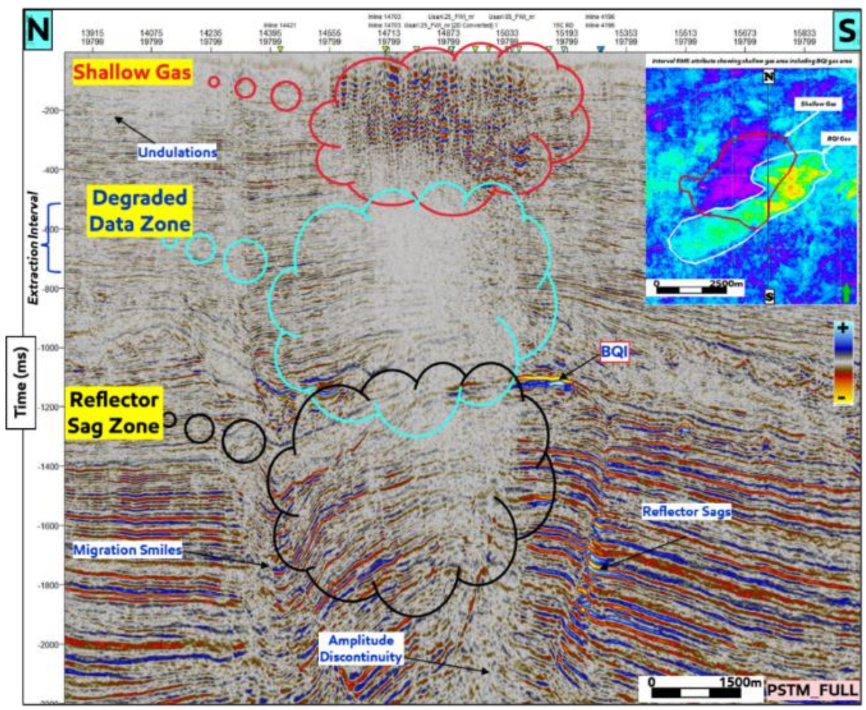


Figure 1: Shallow gas region causes a zone of data deterioration and sags in seismic events

The image above (Figure 1) summarizes the Usari Graben imaging issues. Events below about 1.0 second are pulled down, while events above are mostly wiped out. Above 300ms, bright discontinuous reflections are believed to represent shallow gas zones. This PSTM processed data utilized seismic velocities in areas without well control for migration, and significantly, these seismic velocities picked by semblance method did not see the shallow gas cloud. The velocity picking method may have been such that it could not respond to anomalous velocities, or it may have been seen on few picks that was ultimately removed by smoothing.

The primary objective of the FWI processing was to produce earth models for improved imaging beneath the shallow gas anomalies and within fault-shadows regions by resolving the complex seismic velocities in this area. This paper will demonstrate how seismic imaging and reflection continuity improved due to better resolution and fidelity of velocity and anisotropy models, in the process, reducing reflector sags. The FWI velocity model clearly delineated the location and variability in intensity, size, shape, and extent of the shallow gas anomalies within the area. This high resolution shallow gas delineation enabled careful application of attenuation compensation which enhanced weak amplitudes in deep sections, improved imaging and amplitude fidelity in the wiped out zones as previously observed on the PSTM data.

ExxonMobil's proprietary algorithms allow us to increase the range of frequencies used by full wavefield inversion in order to create maps of subsurface structures close to reality. In most published FWI studies, only the lowest frequency portion (less than 10 Hz) of data using simple simulation physics is inverted, resulting in low-resolution models (ExxonMobil Internet Publication 2018).

1.2 Field Overview

Usari Field is a shallow water field located offshore Niger Delta in water depth of approximately 65ft, in NNPC-MPN Joint Venture acreage operated by ExxonMobil (Figure 1). The field was discovered in 1964. Early exploration, appraisal, and development efforts in Usari relied on old vintage 2D seismic data with sparse well control. Between discovery and now, 51 producers have been drilled to deplete the oil reserves across five producing– BQI, Shallow, Intermediate, Deep, and Graben with different pressure regime and reservoir fluid properties.

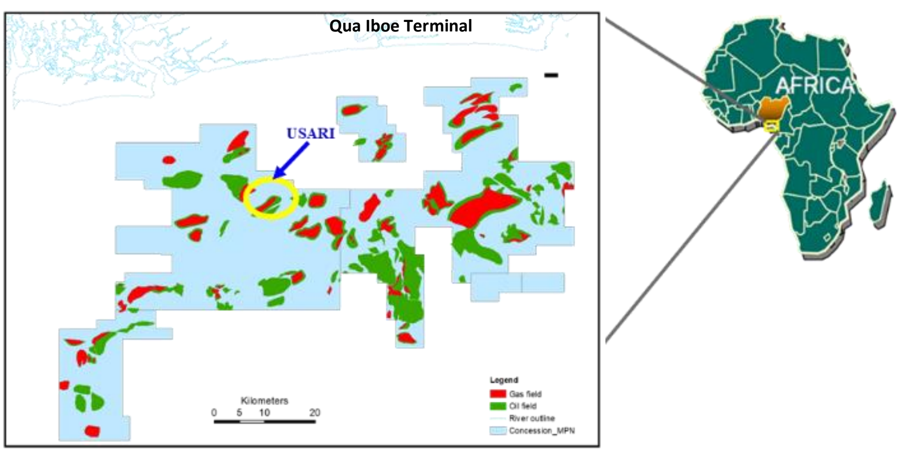


Figure 2: Regional map of Africa showing Mobil Producing JV Acreage with Usari Asset in Highlight

The Usari structure is a complex rollover anticline with two major opposing dipped extensional faults creating the Usari Graben structure. This gently dipping graben is highly faulted, creating numerous fault dependent hydrocarbon traps (Figure 3). The Intermediate and Deep area of Usari is characterized by a three way fault dependent hydrocarbon traps (high-side fault accumulation) and have relatively thick hydrocarbon columns as thick as 600ft. However, significant number of hydrocarbon traps within the Usari Graben have relatively thin hydrocarbon column (<50ft) with the hydrocarbon-water contacts mainly controlled by structural spill points.

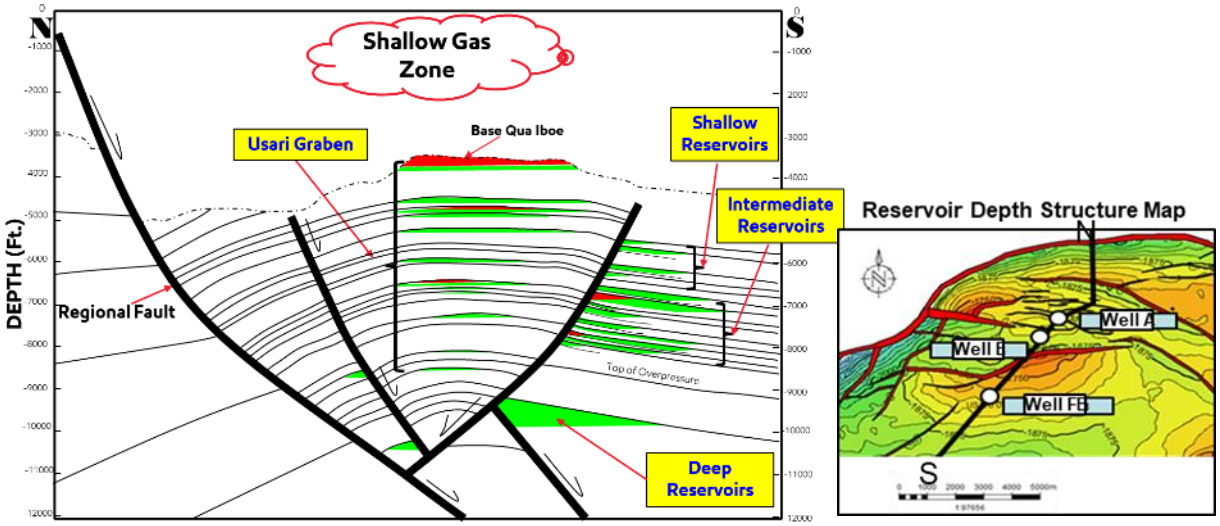


Figure 3: Geologic cross section showing structural and stratigraphic settings of Usari Field with field type log

Stratigraphically, the Tertiary Niger Delta is composed of three major units namely the shale-prone Oligocene to Miocene Akata Formation, the interbedded sands and shales of the Miocene to Pliocene Agbada Formation, and lastly, the sand-prone Pleistocene to Recent Benin Formation. (Kreisa et al 1998). All three formations are present in the Usari Field. The producing reservoirs at the Usari Field are within the Messinian “bedded” Biafra Member, which are primarily fluvial and shallow marine (i.e., shoreface and deltaic) deposits (Buckley, et al., 2002).

This paper aims to show practical examples of the impact of FWI processing in a mature field like Usari. Information deduced from the FWI seismic provided critical insight to the degree of uncertainty associated with prospects under the shallow gas area. These examples re-iterates the immense value of FWI processing in proper reservoir characterization and its impact on re-development investment decisions.

2.0 Methodology

2.1 Usari FWI Application

The FWI workflow is an integrated but flexible pre-migration seismic processing that enables simultaneous estimation of multiple subsurface parameters utilizing raw seismic data including refractions, diving waves, and wide-angle reflections (Tarantola 1984, Pratt et al., 1998). The ExxonMobil FWI processing workflow is an optimization based inversion that tries to obtain a model, which completely describes the observed data (Dave et al. 2009).

The seismic data used for this processing is an Ocean Bottom Cable (OBC) data which totaled approximately 1600km^2 of full fold data with a maximum offset of 6km. The total data processed using FWI technology covers approximately 490km^2 of this area. To achieve the primary objective of this processing, issues that were addressed includes but not limited to resolving shallow gas anomaly velocities, enhance attenuated seismic amplitudes below the shallow gas clouds, noise elimination, multiples attenuation, amplitude preservations, enhancement and maintenance of high frequency content, minimization of imaging artifacts, and ensure a geologically consistent anisotropy model.

The input data is seismic shot gather, initial velocity field, a wavelet, and the acquisition geometry. With this, we simulate seismic shot using the smooth initial velocity model. This is then compared with the initial shot, before generating the residuals. The goal is to reduce this residual to the barest minimum, so that the model shot is comparable to the actual shot in the field. This is done in an iterative manner starting with the low frequency before incorporating high frequencies. In other words, FWI process includes migration with initial background velocity model, demigration using obtained image and initial model, calculation of data misfit, computation of gradient along the wave path of the source of the incident and reflected waves, and background model update (Wang et al 2013).

The migration process ideally repositions seismic events to its true subsurface spatial location (Gray 2015). The degree to which this is achievable depends on the level of geophysical and algorithmic simplifications used (Jones 2014). In this study, both Kirchhoff and Beam migration algorithms were used. Critical to the FWI processing is the velocity model used for migration. The aim here is to create a velocity model that best represents the subsurface, and obtain subsurface parameters (vertical velocity and anisotropy models – delta and epsilon) which provide optimal seismic images and that enhances seismic interpretation. The velocity model was built iteratively where the velocity field was refined with each iteration. Each iteration involves the manipulation of the velocity model and remigration to output gathers for the next iteration. The initial velocity model used is a conventional semblance based velocity field, where RMS velocities were manually picked on a series of lines at regular spacing. These velocities were then converted from Vrms to Vint using Dix equation before being smoothed. The isotropic velocity model then started with a smooth global tomography update, and iteratively add the smaller wavelength details with each subsequent update (Figure 4).

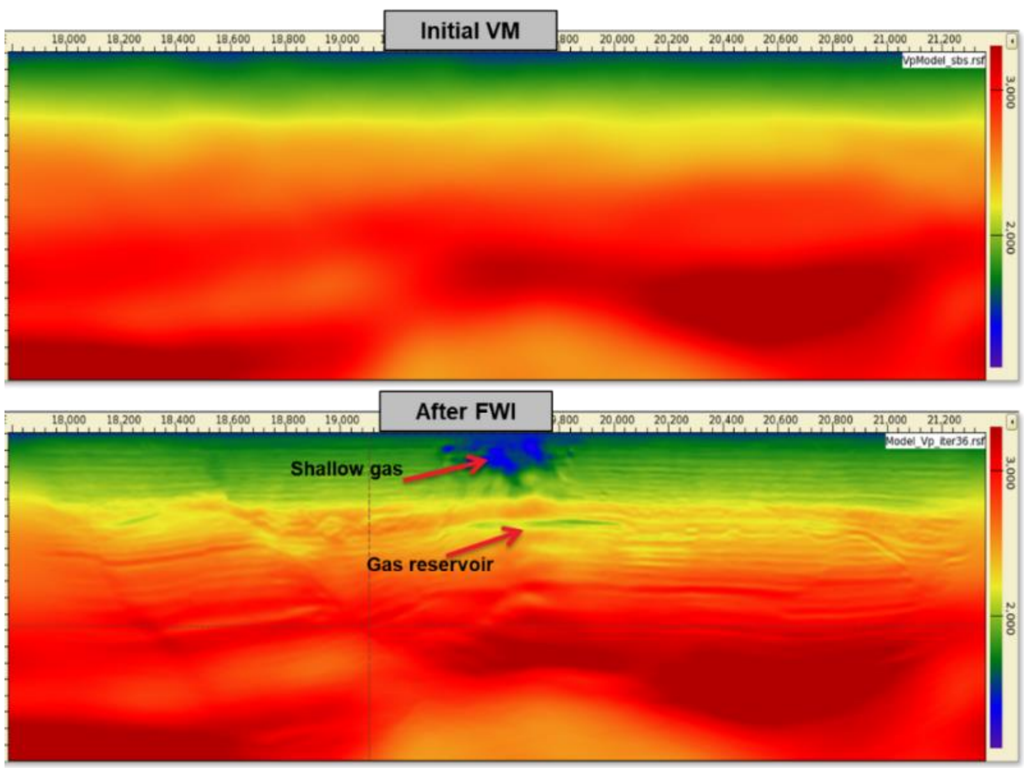


Figure 4: Initial (PSTM) vs Final Velocity Model after FWI application

The existing PSTM velocities above (Figure 4) clearly does not incorporate the shallow low velocity anomaly (gas cloud) creating an image that is unacceptably distorted below it. Though the areal extent of this unresolved anomaly is relatively small, the associated image distortion below it is several kilometers wide. The FWI velocity model clearly shows the locations and variability in the sizes, shapes and extents of shallow gas anomalies within the study area.

The anisotropy modeling strategy involved tying the model to lithology and properly representing the velocity fields that converges at well locations (constrained). In Usari area, within the relatively simple compaction driven section of the field, there is a significant variability in anisotropy which is controlled by the complex distribution of shallow water facies (Gurch et al 2014). An example of this is the Intra Qua Iboe shale with strong velocity/anisotropy contrast with the background. Before integrating the well control/interpretation data, the tomography incorrectly yielded a faster (e.g., than background) velocity solution for these layers, due to cross-feed between vertical velocity and epsilon (Gurch et al 2014). Top and base for the fast and slow IQI layers (Figure 5) were interpreted and inserted into the model, and this allowed the tomography to converge to the correct shale velocity epsilon (Gurch et al 2014). The highly resolved gas anomalies derived through FWI enabled estimation and compensation for attenuation (Gboyega et al 2017), providing further imaging improvements and amplitude fidelity within the graben area.

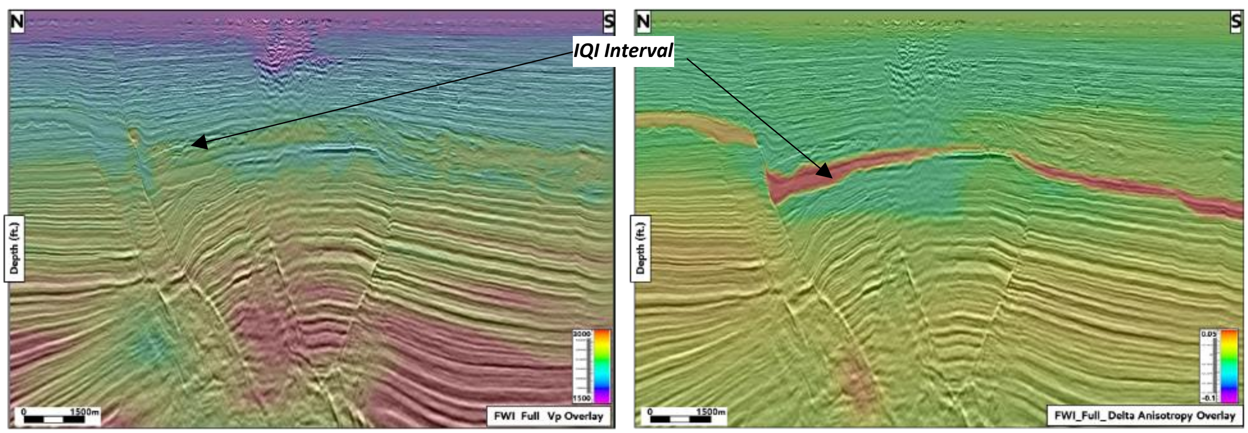


Figure 5: Anisotropy Model in IQI

3.0 Discussion and Results

A holistic evaluation of the impact of FWI processing on some known and unknown imaging issues within the scope and timing of the processing required an approach that prioritized and scaled technical activities relative to business decisions and timing. This includes a clearly defined goals and timeline, with expected deliverables. Efficiencies were notably gained through early engagement with Usari Geoscience team, integrating observations that provided early insight on geologic and well controls.

4.1 Gather Flatness:

One of the common and effective way to qualitatively estimate the uncertainty of seismic images is to compare observations on gathers back to stacks to gain insight into data problems and limitations. Understanding of gather flatness and lateral variability in quality gives interpreter a handle on the data fidelity of the different seismic stacks, and is useful for discriminating and quantifying seismic data limitations. The PSTM gathers only used seismic velocities that attempts to flatten the gathers. This typically exhibit push down distortions mainly due to the assumption that all traces in the Common Mid-

Point (CMP) gather should be processed with the same 1D velocity-time function associated to the CMP location without taking into account lateral velocity changes (Jones 2014). This problem was solved by using a more sophisticated and accurate 3D velocity model to migrate the data resulting in a flatter, higher signal to noise ratio seismic gathers (Figure 6).

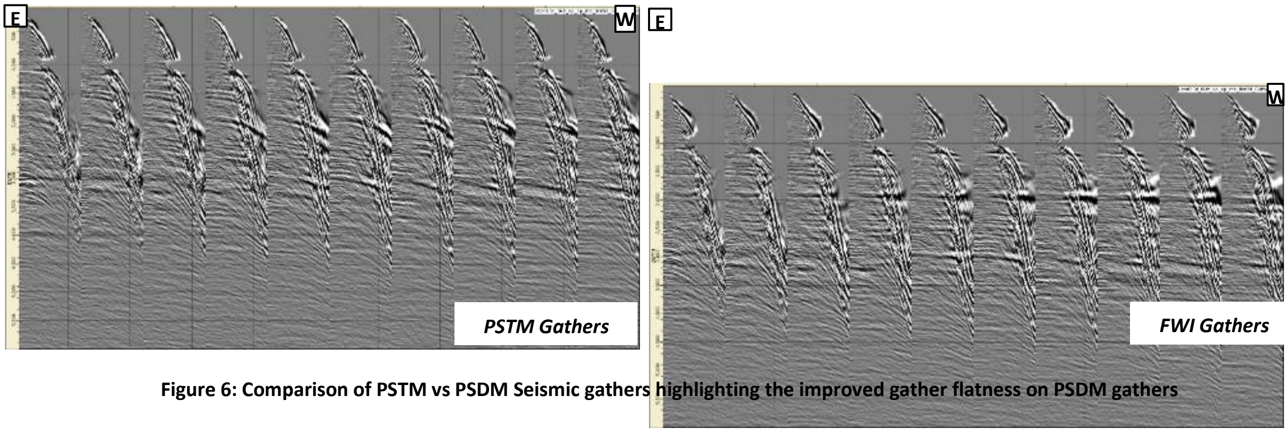


Figure 6: Comparison of PSTM vs PSDM Seismic gathers highlighting the improved gather flatness on PSDM gathers

4.2 Imaging Uplift – Interpreter's Perspective

Overall, seismic imaging and reflection continuity improved due to better resolution and fidelity of velocity and anisotropy models in the vicinity of the fault-shadows, and below the shallow gas clouds reducing reflector sags. Also, weak amplitudes in deep sections were enhanced by careful application of attenuation compensation (Figure 7).

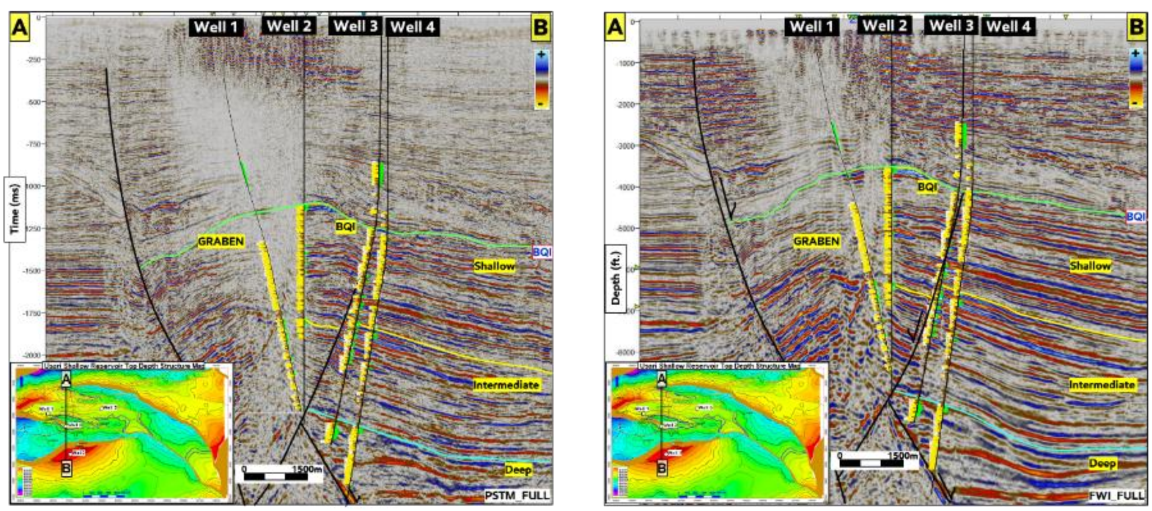
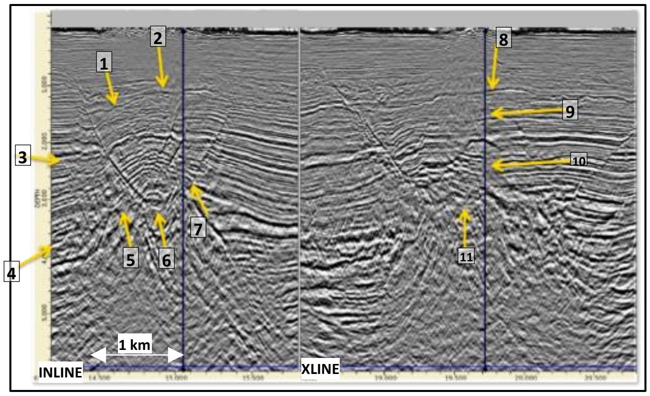
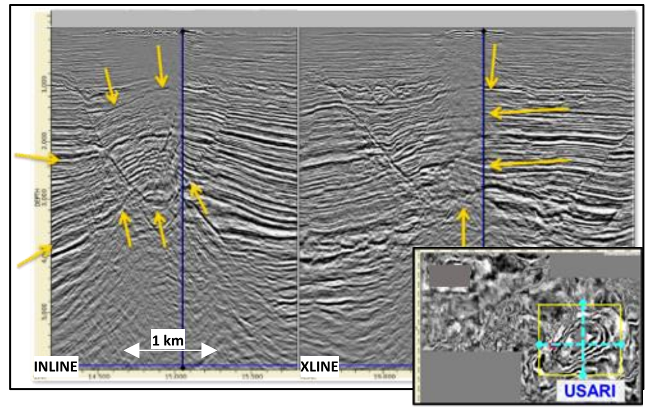


Figure 7: PSTM vs FWI highlighting seismic imaging uplifts

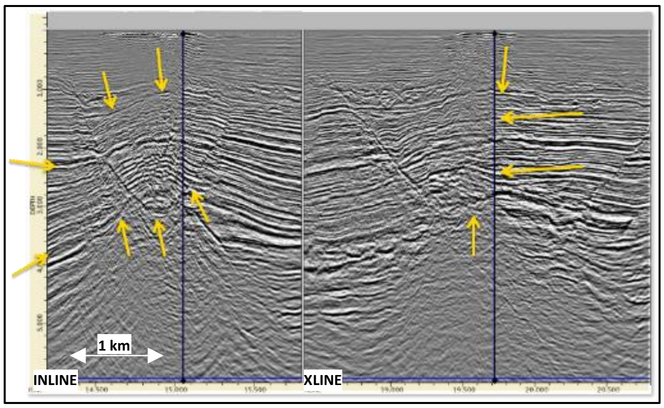
The figures below compares the PSTM image, and the several imaging uplift in the Usari graben after FWI processing. The different imaging issues identified on this seismic lines highlights the FWI uplift. Ranging from non-geologic undulations and kinks to fault shadows (Figure 8). FWI-enabled attenuation compensation provides phase, amplitude and bandwidth corrections which improved imaging and resolution below the shallow gas.



(a) PSTM Image



(b) FWI Image



(c) PSDM FWI Image after attenuation compensation

Imaging Issues on PSTM processed seismic

1. Non-geologic undulations
2. Seismic reflector sag
3. Fault shadow sag & migration smiles
4. False seismic character
5, 6, 7. Deep amplitude attenuation
8, 9. Seismic reflector sag
10. Lack of event continuity / amplitude attenuation
11. Deep amplitude attenuation

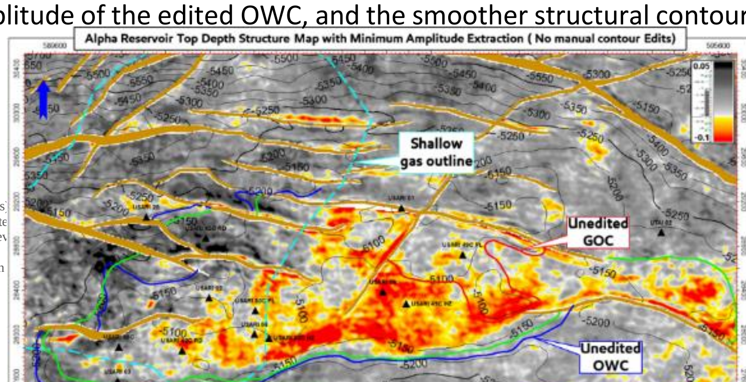
Figure 8: PSTM vs FWI highlighting the numerous seismic imaging uplifts

4.3 Business Impact – Examples from Usari Field

The practical examples below demonstrates the importance of depth imaging in a complexly faulted area like Usari.

4.3.1 Structural Uncertainty – Alpha Reservoir

On the PSTM seismic vintage, an example of structural corrections for a typical graben reservoir impacted by reflection sags caused by the shallow gas anomaly is shown in Figure 9 for the Alpha reservoir below. The black contours in Figure 9a shows the starting depth- structure map, which has been corrected to synthetics in the time domain and further corrected to well picks in the depth domain. Note both the lack of structural conformance to amplitude, and lack of structural continuity in the eastern area where there is a good amplitude signature. Also note the lack of structural continuity in the gas cloud area to the west. The lack of continuity and conformance is likely due to the effects of sag from either shallow gas or local changes in shallower hydrocarbon-bearing intervals. The proposed corrected contours are shown in green (Figure 9a) with the final OWC illustrated in blue in the bottom panel of Figure 9b. Note the good conformance to amplitude of the edited OWC, and the smoother structural contours in both the east and west areas.



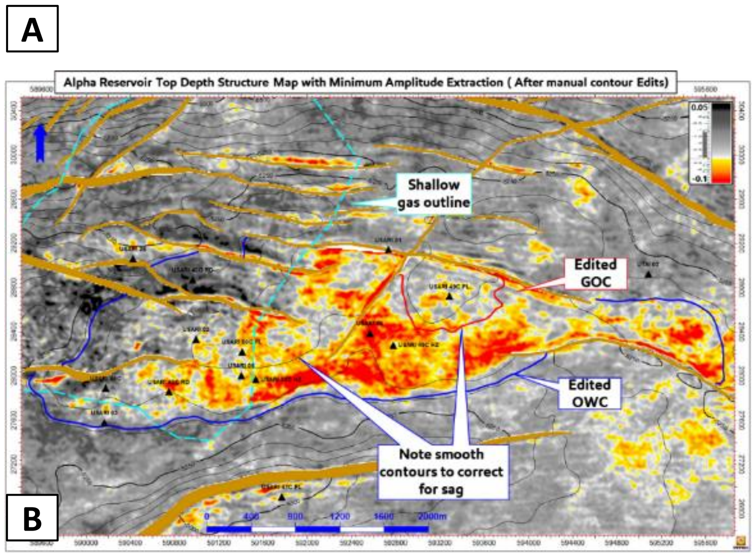
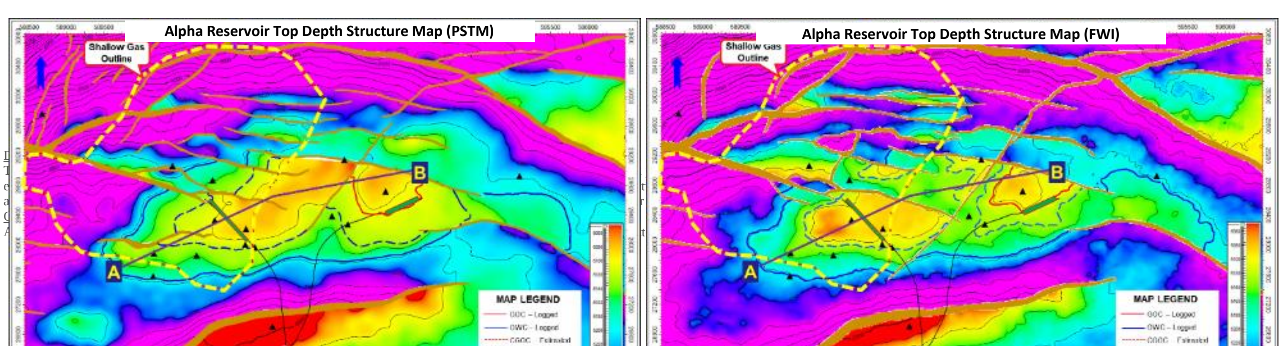


Figure 9: Structural corrections for the Alpha reservoir

A fundamental pitfall for manual corrections as described above is human error, and “over-correction” which can have a significant impact on in-fill drill well opportunities. Also, for both cases (PSTM and FWI), the seismic events converge at well locations, however, away from well locations is where you observe significant variance. The concept of attic oil opportunities depends on placing infill wells above existing perforations provided there is enough upswept oil in the structure. The Alpha reservoir can be divided into 3 main “fault blocks” X, Y, and Z (Figure 10). This reservoir has two active perforations, and a third in-fill well has been proposed to target the attic oil in the X fault block. As defined in the previous “corrected” PSTM image, the X fault block is the highest structurally, and hence, the infill concept was valid as existing perforations cannot effectively drain the oil left above them mainly in X fault block.

The FWI depth processed image however gave an insight into the impact of this structural uncertainty on the drill well opportunity, making the investment potentially uneconomic. Structurally, on the FWI seismic, the X fault block is spatially lower than the other Y and Z fault blocks, placing most of the hydrocarbon pore volume in the fault block within the drainage reach of the existing perforations. Estimating the upswept volume left in the X fault block reduced by a factor of 5X, making the infill well uneconomic. This new understanding could also explain the high rate of volume recovery in the existing perforations in this reservoir.



X

Y

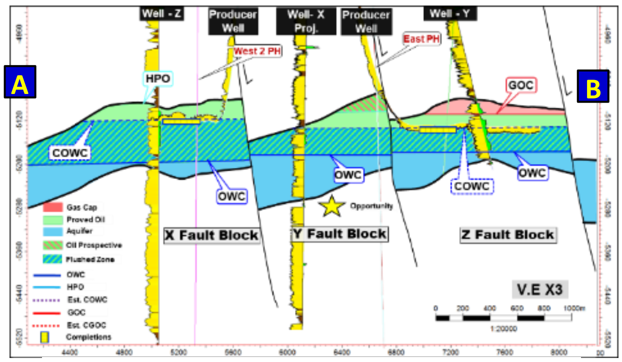
Z

X

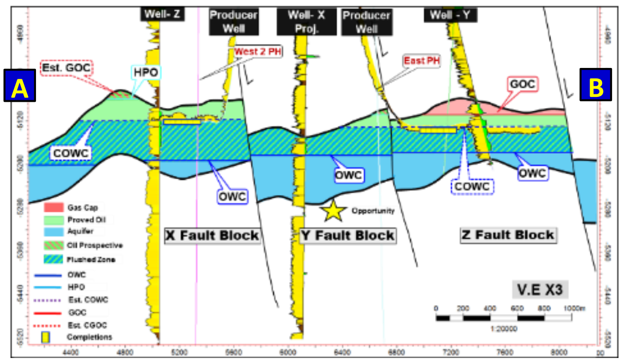
Y

Z

(b) Alpha Top Depth Structure Map (FWI)



(c) Alpha Structural Cross Section (PSTM)



(d) Alpha Structural Cross Section (FWI)

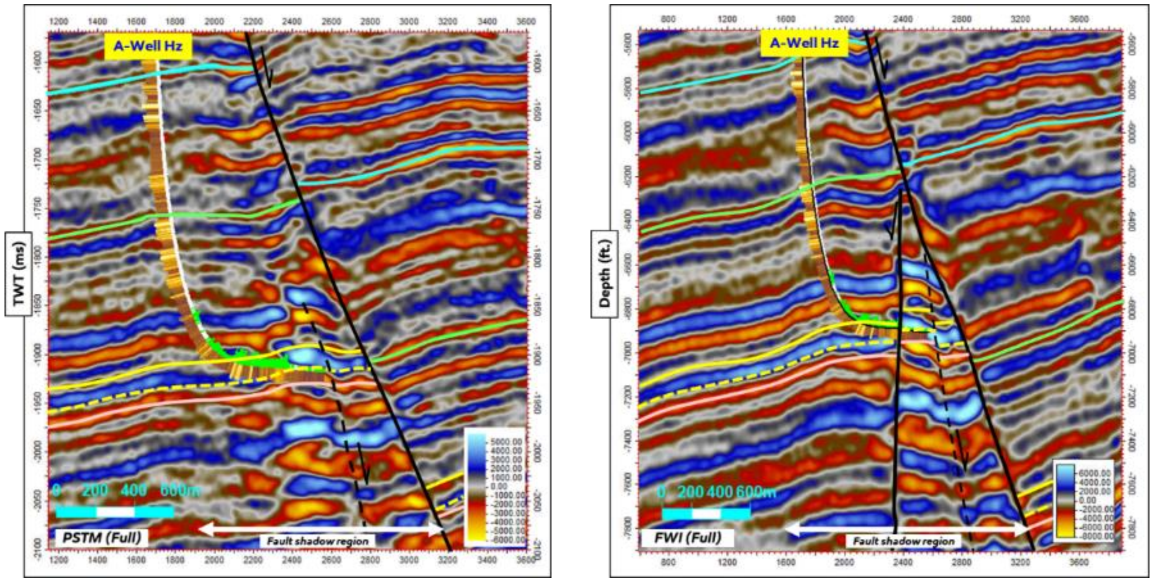
Figure 10: Usari Alpha reservoir describing the impact of structural uncertainty on drill well opportunity

4.3.2 Understanding Production Behavior – Beta Intermediate Reservoir

The Beta reservoir is one of the numerous high-side fault dependent traps in Usari, characterized by significant hydrocarbon column height and good amplitude control on the areal extent of hydrocarbons. Based on log and pressure analysis, an original oil water contact (OWC) was interpreted which corresponds nicely to the seismic amplitude terminations. Also, the original gas-oil contact (GOC) was logged by two wells. Post production wells show possible gas movement at a rate that was expected based on the withdrawal and aquifer strength.

The Beta reservoir has been producing since 1997, and wells have been strategically placed spatially to optimally sweep the reservoir. To the east of the reservoir, A- Well was drilled and completed with a long lateral in order to maximize contact with the reservoir. This well quit unexpectedly on high gas-oil ratio (HGOR) trend that was not observed on the other producer well (B-Well) west of the reservoir, despite it being spatially shallower than the A-Well. An up-dip re-drill of A-Well proved to be successful, with the well streamed without the HGOR that disrupted production from the old well. This is counter intuitive, as you would expect a well closer to the original GOC to have a higher GOR than the down-dip counterpart.

Comparing the PSTM seismic data that was used to drill A-Well to the new FWI seismic data gave an insight as to where the source of the gas might be. The figure below shows two seismic cross sections (PSTM vs FWI) along the A-Well.



(a) PSTM_ Full Seismic Stack (b) FWI_ Full Seismic Stack

Figure 11: Seismic cross section along A-Well Hz on the PSTM and FWI data

On the PSTM seismic (Figure 11a), it is difficult to interpret the antithetic fault, as this was understandably interpreted as a seismic artifact due to its very high angled nature, lack of clarity, and being located under the high-side of a major fault with distorted reflections due to fault shadow issues. The FWI seismic however clearly imaged this fault, by resolving the velocity anomalies around the fault shadow area (Figure 11b). This fault proved to be very significant as it potentially cross-juxtaposed the deeper Gamma reservoir with the Beta reservoir where the A-Well was completed. This hypothesis suggests the well as shown in Figure 12 was completed across the fault, into a gas encroached zone in the Gamma reservoir, thereby explaining the source of the gas that flooded the well. By re-drilling up-dip of the A-Well, without crossing the antithetic fault, the well was able to drain the oil in that area without the HGOR observed in the previous well. The re-drilled well quit on high water cut years after streaming with a total production of ~5 MBO.

In this example, the FWI seismic would have clearly helped the team in optimal well placement of the A-Well Hz, saving the company the cost of the re-drill.

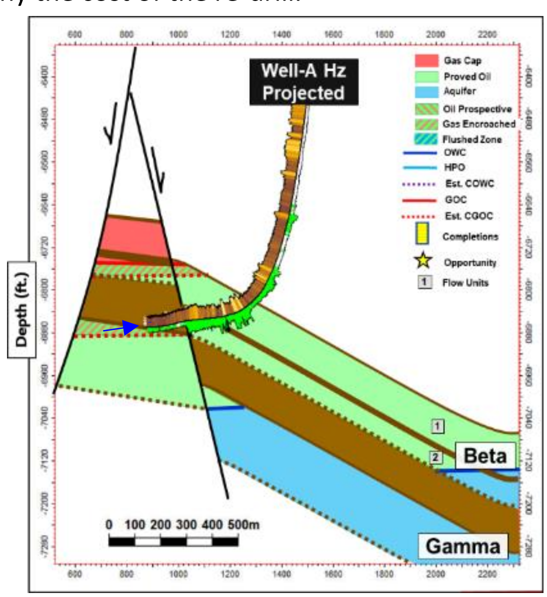


Figure 12: Schematic cross section along Well-A Hz highlighting the impact of drilling across the antithetic fault

4.0 Conclusion

We have used examples from Usari field to demonstrate the value and imaging improvements gained by FWI application. FWI is a key technology to producing a reliable image of the subsurface in an image-challenged environments, such as the Usari area where shallow gas reservoirs coupled with complex faulting causes significant velocity and anisotropy variations.

Analysis of the impact of FWI processing technique involved comparing the existing PSTM data to the new depth migrated data, highlighting the key changes and improvements gained. As earlier stated, a key component of depth migration is the ability to accurately represent the subsurface parameters that predicts the velocity and anisotropy fields. In this case, the FWI velocity model clearly delineated the location and variability in intensity, size, shape, and extent of the shallow gas anomalies within the area. This high resolution shallow gas delineation enabled careful application of attenuation compensation that enhanced weak amplitudes in deep sections, improved imaging and amplitude fidelity in the wiped out zones observed on the PSTM data. Seismic imaging and reflection continuity improved due to better resolution and fidelity of velocity and anisotropy models in the vicinity of the fault-shadows, and below the shallow gas clouds reducing reflector sags.

Overall, with advances in computing power, depth imaging in environments with complex structural and stratigraphic variability is a necessity, and can be achieved with less time and resource compared with what was achievable ten years ago. The simplicity and approximations that time migrated seismic offers simply cannot accurately capture subsurface velocity field complexities. Discussed in this paper are two examples of the business impact of FWI processing from an interpreter's perspective on subsurface reservoir characterization with respect to reservoir connectivity, resource estimation, well placement, and understanding production behavior. It presents information deduced from the FWI seismic that were not imaged on conventional processed seismic dataset and which re-iterate the immense value of FWI processing in proper reservoir characterization and its impact on re-development investment decisions.

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