4D FWI – Learnings from a towed streamer case study on the Usan field

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In the last two years the industry has seen a paradigm shift with the advent of Full waveform inversion (FWI)imaging in 3D seismic data processing projects. Fundamentally this is a fairly simple process as the image is merely a directional derivative of a velocity model, the resolution of which is largely controlled by the maximum frequency of the FWI and of course the subsurface properties. As FWI is an iterative least squares solution of the full wavefield, it has the ability to provide cleaner products over an extended coverage as it uses primaries and multiples. FWI imaging has also enabled turnaround time for projects to be significantly reduced.

Initially there was some skepticism about the amplitude fidelity of such volumes, but through a series of examples, the industry has accepted the technique as either an alternative solution, or in some cases as the primary interpretative product.

Despite the progress made, there are still very few published examples of using FWI imaging in 4D. In this paper we show the application of this technology to show a towed streamer example offshore Nigeria. We will share examples of parallel 4D FWI (run FWI on each 3D and subtracting) versus a joint 4D FWI scheme, which produces equivalent results, but requires only half the number of total iterations per frequency relative to the parallel approach. We then compare the results of the 4D FWI with a conventional 4D processing workflow, discuss the advantages and disadvantages of each and also highlight future considerations.

We wish to thank TGS and Bulwark for their support and Exxon permission to publish these results.

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Emerging Technologies and Current Application in Exploration and Production, Innovations, IoT, Data science, AI and Machine Learning, Modern Trends and Challenges in Oil & Gas Industry

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1.0 Usan field overview:

Usan is a deep-water field offshore Niger-Delta in a water depth of about 800m, in OML 138 (Fig. 1). The field was discovered in 2002 by an exploration well. Eight appraisal wells were drilled between 2002 and 2005 leading to first oil in February 2012. To date, 22 producers, 10 gas injectors, and 6 water injectors have been drilled to deplete the oil reserves across the producing intervals (Onyido et al, 2017).

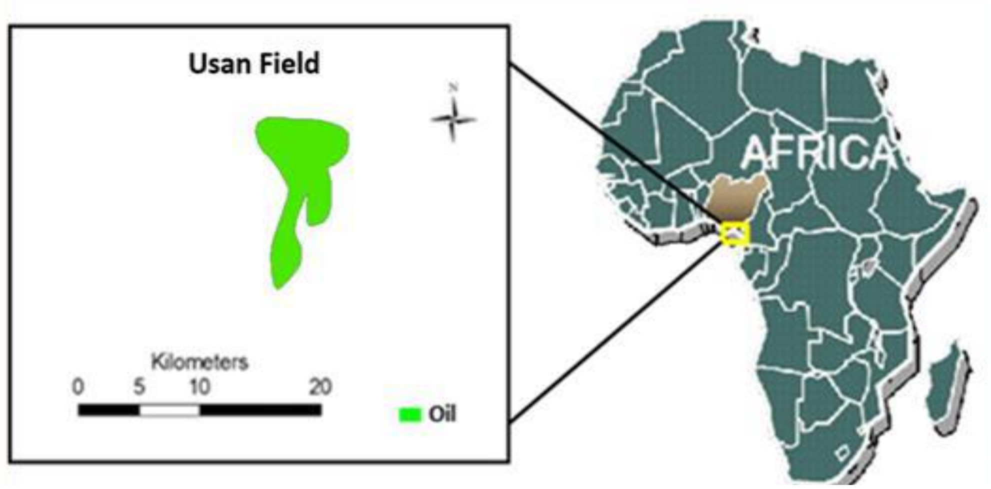

Figure 1: Regional map of Africa showing location of Usan Field

The hydrocarbon traps in the field are a combination of structural and stratigraphic features, with a prominent NE-SW trending shale cored anticlinal ridge (Fig. 2). Draped On the flank of this ridge are Upper Miocene deep water channel complexes that trend perpendicular to the E-W trending post depositional extensional faults (Amadi et al, 2016). This structural and stratigraphic configuration created series of highly compartmentalized reservoirs, with inherent high cost of development, due to increase in well count needed to optimally drain the reserves (Olatunbosun et al, 2019).

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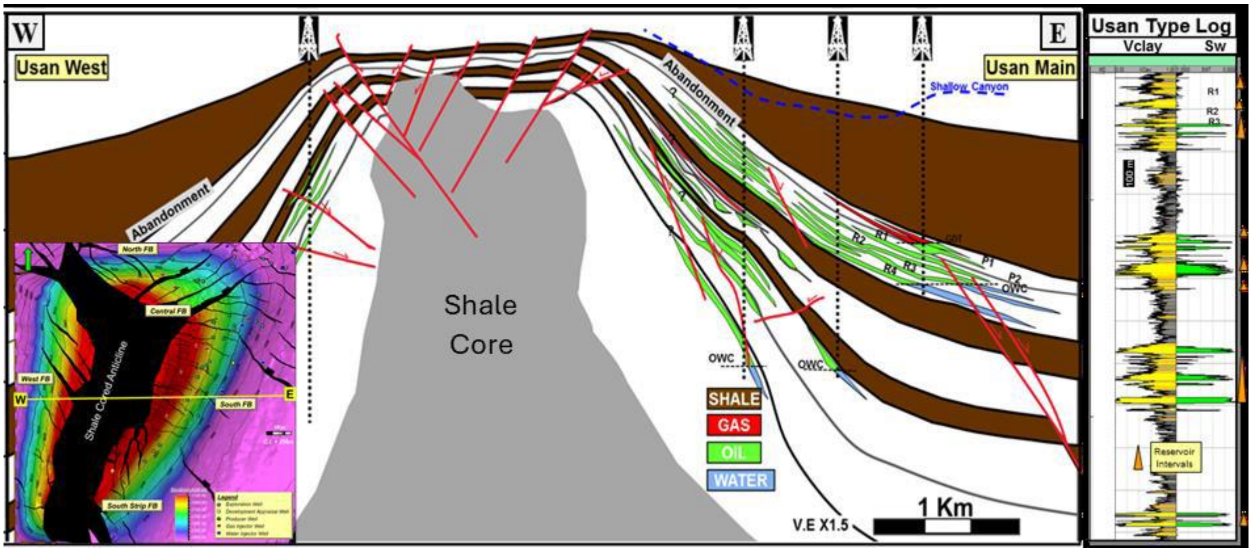

Figure 2: Geologic cross section showing structural and stratigraphic settings of Usan Field with field type log (Olatunbosun et al., 2019)

2.0 Introduction:

A 4D monitor streamer survey was recently acquired in the field to serve as a reservoir surveillance tool for identifying and maturing drilling opportunities. After acquisition, 4D co-processing of baseline and monitor surveys was done with a secondary objective of improving current imaging challenges in seismic data.

The industry has a long track record of 4D processing with significant uptake of the technology in the late 1990’s / early 2000’s. As we have become more proficient with our tools, so have we added complexity. The processing has evolved from DMO-PSTM flows, through PreSTM and today’s flows routinely use PreSDM. In addition to the evolution of the migration algorithm used, the pre-processing have also evolved, the advent of deghosting in early 2010’s changed the look of seismic datasets in both 3D and 4D. moving to 3D demultiple and true 4D processing steps. The result of all these changes means the overall turnaround for 4D projects remains a constant.

The industry has recently seen a paradigm shift with the use of FWI imaging in 3D (Mao et al). FWI Imaging is, in its simplest form, a directional derivative of the velocity model, the resolution of is limited by the maximum frequency of the FWI used in the model building process and the cell size of the model update.

Despite some impressive images, there remained some skepticism about the amplitude fidelity of such volumes, but through a series of examples, the industry has accepted the technique as either an alternative solution, or in some cases as the primary interpretative product. As these products can be defined using either solely raw/minimally processed data or also pre-processed (e.g. with demultiple applied), these FWI images can be obtained in far faster turnaround relative to conventional processing projects.

Whilst there has been success in 3D, the number of examples of 4D FWI imaging remain scarce.

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3.0 Methodology:

DM FWI uses both diving wave and reflections simultaneously to derive an accurate velocity field. DM FWI is insensitive to cycle skipping and robust to data with low S/N with proven success to produce a structurally conformable update to the velocity model (Mao, et al., 2020,. DM FWI updates the velocity models by maximizing the similarity between the observed data d(t) and the synthetic data u(t) that is measured by the following objective function:

$$E(m) = \sum_{s,r,j} c(s,r,j) \qquad (1)$$

where c(s,r,j) is the local cross-correlation of an observed data d(t) and a dynamically matched version of the synthetic data u(t) simulated using model m, through local amplitude normalization, thus making the data matching less sensitive to amplitude discrepancies due to noises, etc

The proposed 4DFWI algorithm (Gao et al, 2024) that jointly inverts baseline and monitor datasets intends to minimize the following objective function:

$$\begin{aligned} E(m_{base}, m_{monitor}) \\ &= \sum_{s,r,j} \left[\frac{1}{2} - \frac{1}{2} c_{base}(s,r,j)\right] \\ &+ \sum_{s,r,j} \left[\frac{1}{2} - \frac{1}{2} c_{monitor}(s,r,j)\right] + \alpha \left|\left|R(m_{base} - m_{monitor})\right|\right|^{p} \qquad (2) \end{aligned}$$

where R is a regularization function which could optionally be a mask function, α is the damping coefficient which defines the relative weight of the third term on the right hand of Equation (2), and p is either 1 or 2, the norm of the 4D model. Minimizing the first and second term on the right hand side of Equation (2) is equivalent to maximizing the 3D DM FWI objective function defined in Equation (1) using either dataset respectively, and the choice of ½ is to normalize the terms numerically within [0,1] for convenience. The third term is a 4D model regularization, penalizing the difference between the two models being jointly updated. The final baseline and monitor models are the models with minimum difference between them (measured in L1 or L2 norm), yet each predicts the respective dataset well. One of the advantages of 4D joint inversion is that the two datasets do not have to be aligned perfectly, although it is assumed that the two acquisition geometries are relatively near each other spatially.

For gradient-based FWI, the algorithm is realized by alternative updates between the baseline and monitor models by deriving gradient with respect either of them at a time. After one model is updated for n iterations where n $\in [1,3]$ in our practice, it will be used and fixed inside the 3rd term on the right hand of Equation (2) for the next alternation.

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4.0 Results:

Initially we focused on generating a velocity that was suitable for migrating all vintages used in the 4D processing. For early frequency bands, we used data with minimal processing applied. However, as we moved to the frequency bands in excess of 16 Hz, we used data with a more rigorous processing applied (including demultiple). Throughout the inversion process, stringent Quality Control (QC) measures were implemented, ensuring convergence in both the data and image domains. Quantitative assessment in the data domain scrutinized the mismatch between forward-modeled shot gathers and input shot gathers, while multiple image domain QC methods, including the evaluation of the flatness of common image gathers, were employed. Directional directives were applied to the FWI velocity model, producing FWI Imaging after each frequency band, which was then compared against the corresponding Pre-Stack Depth Migration (PSDM) image. The output from the 3D model building was a very geologically consistent model and is shown in both figure 3 (vertical section) and figure 4 (depth slices).

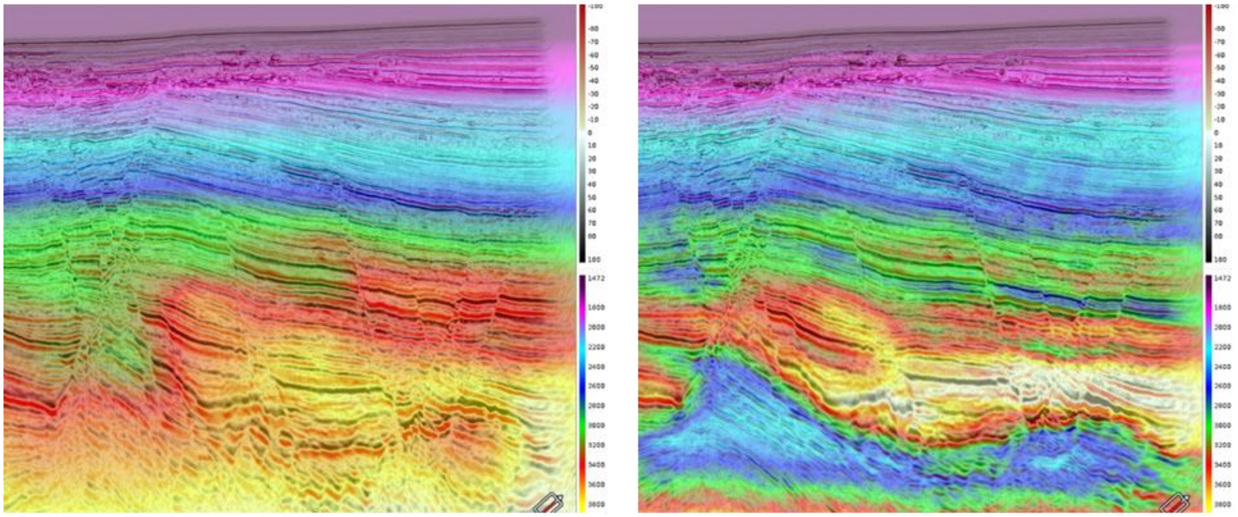

Figure 3 – Legacy (left) and update (righ) velocity models overlaid on migrated seismic data

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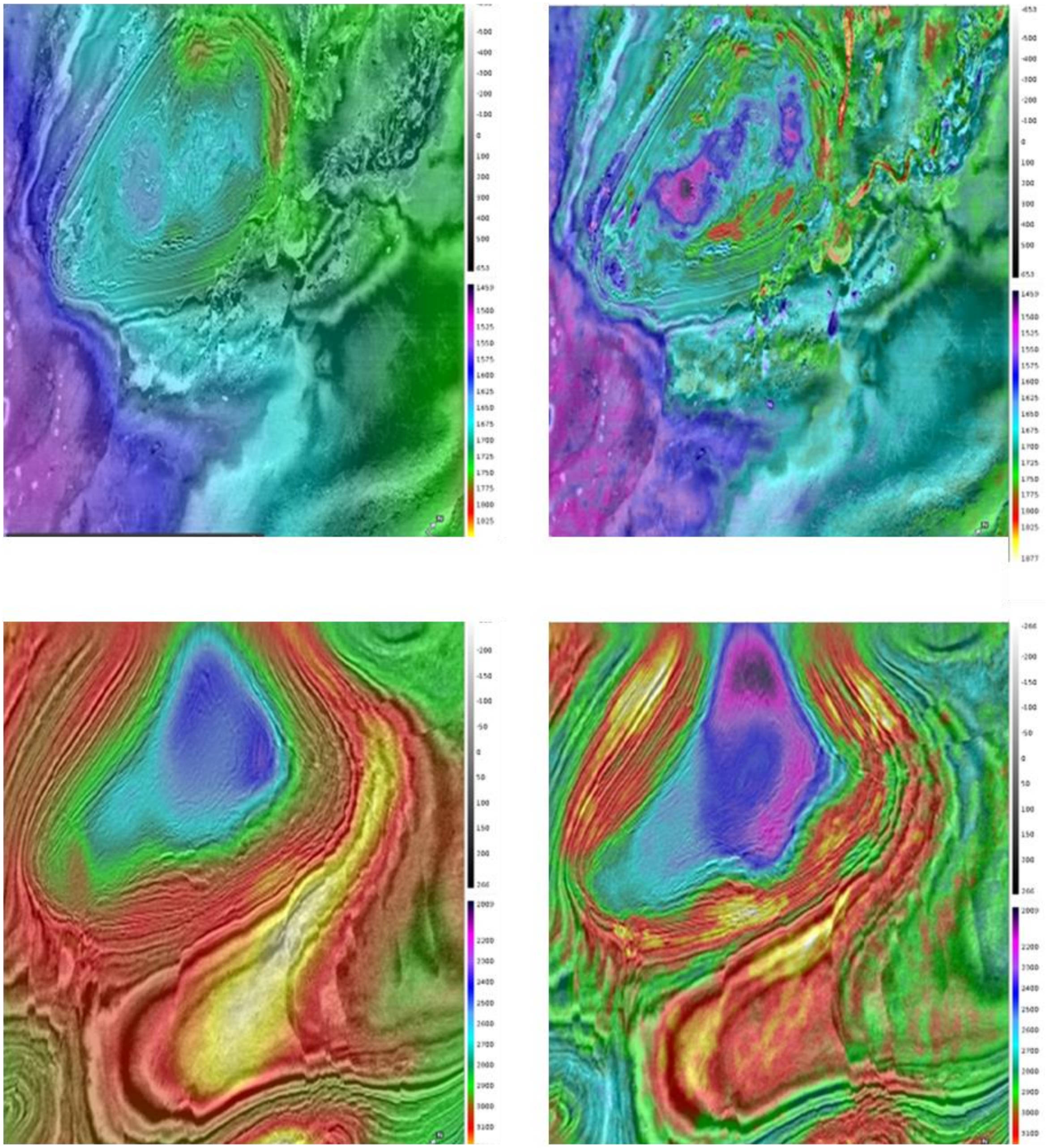

Figure 4 – The 1km (top) and 3km (bottom) depth slices from the legacy (left) and update (right) velocity models overlaid on migrated seismic data.

During the processing of the 4D data, the predicted timeshifts were observed and we embarked on a test to evaluate whether it was possible for FWI to also observe these changes. As proof of concept, we took the penultimate band from the 3D FWI (16Hz) from the 3D velocity model build and re-ran the 20Hz band on a limited area (11 sail line swath) on both the base and monitor surveys. datasets. This provided a result that was very encouraging. We recognized the deficiencies in this very quick proof of concept test and set about testing in a more robust way.

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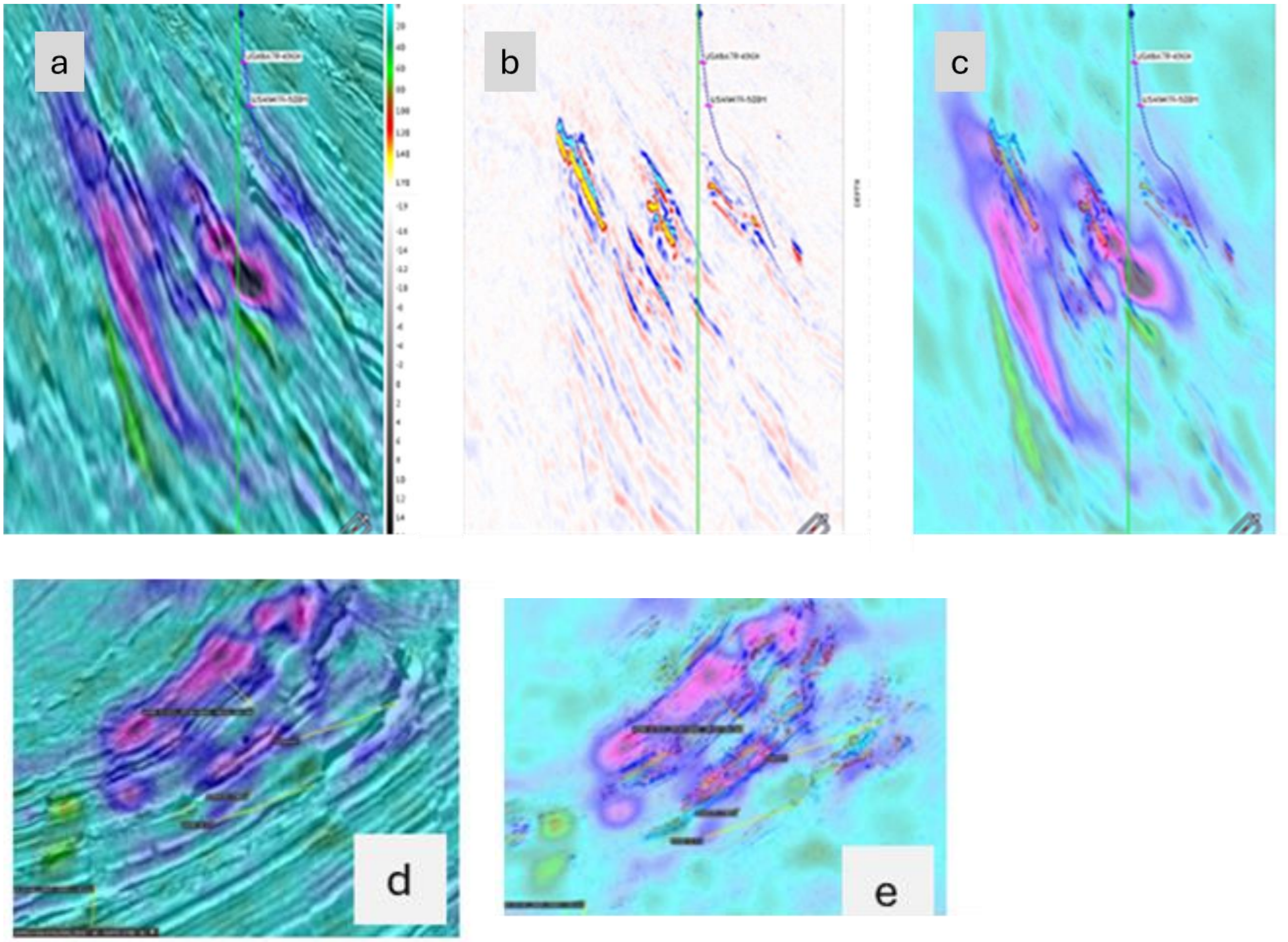

Figure 5 – Streamer – 3D stack & 4D FWI (a), 4D difference (b), 4D difference & 4D FWI (c), timeslice of data show in figure a (d), timeslice of data show in figure c (e),

Given the success of the initial test we decided to use our 4D Joint Inversion FWI on a larger portion of the 4D area. Prior to running the inversion, we performed some basic 4D processing on the data to ensure we were inverting for the changes in the subsurface rather than geometrical issues in the various acquisitions. Much like in conventional 4D processing, where 4D binning is performed on CMPs, we perform a pseudo 4D binning on shots to ensure we are inverting for similar data. We began the inversion process at the first frequency band and repeated the frequency bands of the 3D FWI model build. The use of the Joint inversion produced similar, but sharper results relative to the parallel 3D FWI approach . The advantage of this joint inversion is that it requires far fewer iterations than two independent 3D FWI runs and the use of the 4D within the inversion stabilizes the results (figure 5).

We are currently assessing the value of extending the frequencies used in our 4D FWI.

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5.0 Conclusion:

We have found that our 4D FWI produces anomalies in coincident locations as 4D features on conventionally derived reflectivity images. This gives us confidence that FWI can produce reliable 4D signals but in a fraction of the time and effort. This is true of both the dual 3D approach and the joint 4D approach. This also gives credence to the use of amplitudes from 3D FWI image for exploration purposes.

We are currently in the process of evaluating the results in greater detail.

6.0 Acknowledgements:

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