Advanced Seismic Imaging Unlocking Potentials in Exploration and Development – Case Study Onshore Niger Delta

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ABSTRACT

The dynamics of a changing global energy outlook with attendant issues surrounding global warming, reduction of forms of greenhouse gases, and the quest for accelerated energy transition cannot be overemphasized. It becomes imperative that the oil and gas industry reduce her surface seismic acquisition footprint as much as possible where this is feasible and apply advanced seismic processing technology to harness hydrocarbon potentials in development fields and unexplored areas using existing seismic datasets. The advanced seismic processing technology deployed is Reverse Time Least Squares Migration RTLSM, while the processing applied on the legacy volume was conventional Reverse Time Migration. This paper presents results of RTLSM to address near field exploration imaging challenges in structural definition and event continuity among others using existing seismic dataset without performing any velocity update. This implies the seismic velocity used in the legacy RTM seismic is the same used in the RTLSM processing. RTLSM seismic volume showed, improved imaging in faults, stratigraphic and event continuity at shallow and deep, better amplitude consistency with structure, improved signal to noise ratio and broadband width and better wavelet signature (less sidelobes). A comparative quantitative seismic diagnostic analysis carried out on the legacy RTM and the new RTLSM seismic volumes, reveals acquisition footprints and clipping in the legacy RTM volume were largely removed among other diagnostics. It is the aim of this paper to share this interesting results in deploying high end seismic processing technology to unlock hydrocarbon potentials using existing seismic data sets.

Keywords: RTM, Non-iterative RTLSM, Deep plays, AVA/AVO compliant gathers, Niger Delta.

INTRODUCTION

The field is in the swamps of the Niger Delta (Figure 1). Exploration team main challenge is with interpretation of deep plays with suboptimal resolution in faults and events continuity. Legacy RTM and PreSDM processing had been applied across the field earlier and was successfully used for the maturation of conventional amplitude-supported plays in the area. However, the RTM seismic volume is suboptimal for the imaging/maturation of the deep plays situated in the upthrown blocks behind major faults within outer shelf gross depositional environment with moderate – low internal net to gross and mud-prone channels. The pre-stack gathers from the PreSDM processing were also suboptimal for Quantitative Interpretation QI. The RTLSM reprocessing of the seismic data was initiated to optimize imaging (fault delineation & event continuity) and deliver QI compliant gathers for credible AvA work in support of the maturation of deep leads.

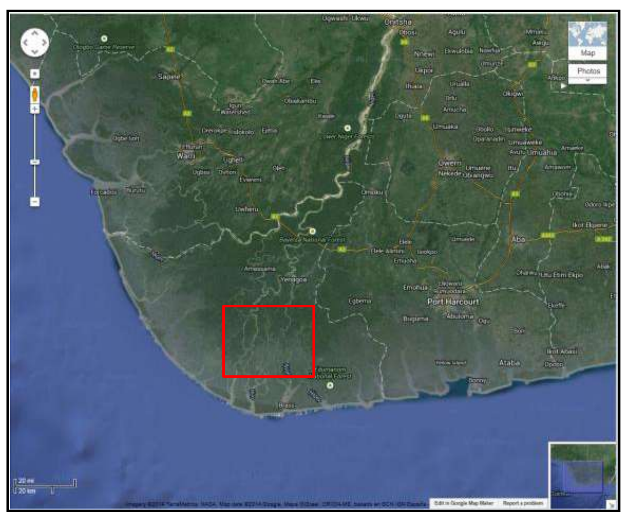

Figure 1: Location map. The study area is within the red rectangle (Source: Google Maps).

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METHODOLOGY

Seismic migration is a technique employed in imaging of geologic interfaces in the subsurface and attempts to place recorded seismic reflection in their true spatial positions. Reverse Time Migration (RTM) and Reverse Time Least-Squares Migration (RTLSM) are both two-way wave equation migration that produces seismic wavefields of high resolution when compared with ray-based methos and one-way wave equation-based methods. High resolution seismic data is a primary driver in exploration and development of complex subsurface structures to unlock hidden potentials.

RTM gives higher accuracy than other less robust/cheaper methods for imaging of steep dips. RTM uses adjoint operator, which is not the same as the inverse, thus amplitude problems are generated which can be solved by applying a least-squares scheme in the migration. Least-squares migration (LSM) can potentially, reduce migration artifacts and improve lateral resolution (Liu *et al.,* 2019). LSM uses iterative methods to match the observed data for every iteration and can solve the amplitude inaccuracy of RTM. Therefore, RTM can be implemented by a least-squares scheme, which is LSM (Yang *et al.,* 2017).

Reverse Time Least Squares Migration (RTLSM) is believed to generate superior images compared to conventional RTM and Kirchhoff imaging from a structural and amplitude perspective. Seismic imaging also suffers from illumination at targets based on focused energy. With the recent advances in industry scale RTLSM, improvements in this scheme helps to produce gathers and stacked images suitable for amplitude interpretation through preconditioning constraints which can reduce noise, migration swings and cross cutting noise that corrupt the reflector amplitudes (Duveneck *et al.,* 2019; Chandran *et al.,* 2019).

LSM Theory: The theory of modelling recorded seismic data abounds in numerous literatures and publications. Here we attempt to reproduce the basic concepts from those existing materials.

The forward modeling operator that relates the reflectivity model m to scattered seismic data d can be represented by

$$d = Lm \qquad 1$$

where, L represents the forward modeling operator. The migration operator is the adjoint of the forward modeling and can be represented by (Claerbout, 1992):

$$mi = L^T d \qquad 2$$

where, mi is the migration image. Conventional RTM method, employ the adjoint modeling operator, by reversing the forward wave propagation effects from the data.

For a better reflectivity image, the imaging problem can be represented as a least square inversion problem which requires the minimization of an objective function. LSM solution is obtained by minimizing the objective function S(m) which is the squared difference between the forward modelled data Lm and the recorded data d (Equation 1).

$$\mathbf{S(m)} = \frac{1}{2}|\mathbf{Lm} - \mathbf{d}|^2 \qquad 3$$

The normal equation which is solved to obtain the optimal image is given in equation 4.

$$L^T Lm = L^T d \qquad 4$$

In this equation $L^T L$ is the Hessian of the linearized modeling operator. L^T is the imaging (migration) operator (adjoint of L) and L is the linearized modelling (demigration) operator (Duveneck, 2021).

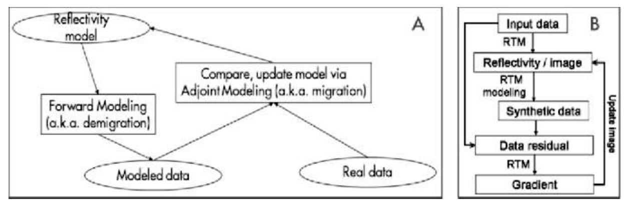

Figure 2: (A) shows a schematic diagram of how LSM works and (B) is Dong et al., 2012 workflow for implementation of LSM. The gradient is calculated by using conventional RTM with the data residual. The gradient is used to adjust the reflectivity model, the process iterates up to a certain level of residual.

Basically, LSM applies the inverse of the Hessian matrix as the RTM adjoint operator (Wu *et al.,* 2021). This application results in the removal of source signature blurring and uneven illumination producing image with higher resolution and more balanced amplitude than the conventional RTM image. There are numerous proposed improvements for LSM (Dong *et al.,* 2012; Huang *et al.,* 2017; Wang *et al.,* 2016).

Advanced Imaging Solution: Due to time constraints, the denoised gathers and the migrated velocity from the immediate legacy processing was used as input into the more advanced seismic imaging solution – Reverse Time Least Squares Migration RTLSM. The implication here is that there was no new velocity model building done. Non iterative RTLSM was implemented for new stack volume and pre-stack gathers.

One likely solution without this advanced high-end seismic imaging solution would have been to acquire new seismic data across the field and this comes with its attendant high-cost implication and minimal impact on the environment.

RESULTS & DISCUSSION

The summary of the results of the non-iterative RTLSM processing and comparison to legacy RTM for stacks and to legacy pre-stack PreSDM gathers are presented in figures 3 to 5 below.

RTLSM vs RTM Stack: Results reveal significant structural and stratigraphic uplift in the new non-iterative RTLSM seismic volume both in the shallow and deep. The key exploration challenge was met with faults better resolved, event more continuous and stratigraphic expressions better defined. Figure 3 shows the impact of the new RTLSM volume over the RTM.

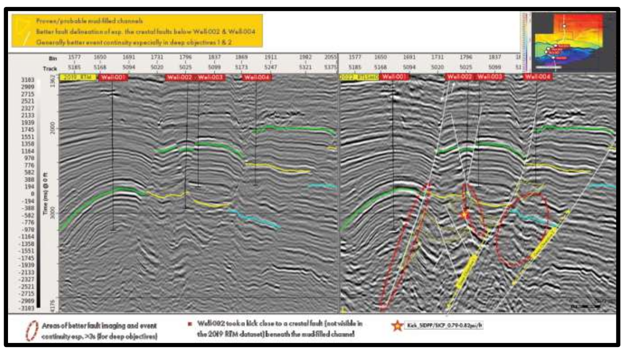

Figure 3: RTLMO (on the right) shows significant improvement and better imaging in the deep including unveiling of probable mud filled channels.

Diagnostic Comparison – RTLSM vs RTM Stack: High-level QC screening was carried out on the RTM and non-iterative RTLSM 3D seismic datasets. This comparison (using the same AOI) provides a consistent basis for comparison between different vintages of processing (legacy and new datasets). It produces an automated report as a framework to structure further manual analyses, and share outcomes with team members, partners, assurers, and decision makers. Seismic Diagnostic analysis reveals that the non-iterative RTLSM seismic volume is quantitatively better than the RTM seismic volume with improved SNR. Figure 4 shows part of the diagnostics impact of the non-iterative RTLSM.

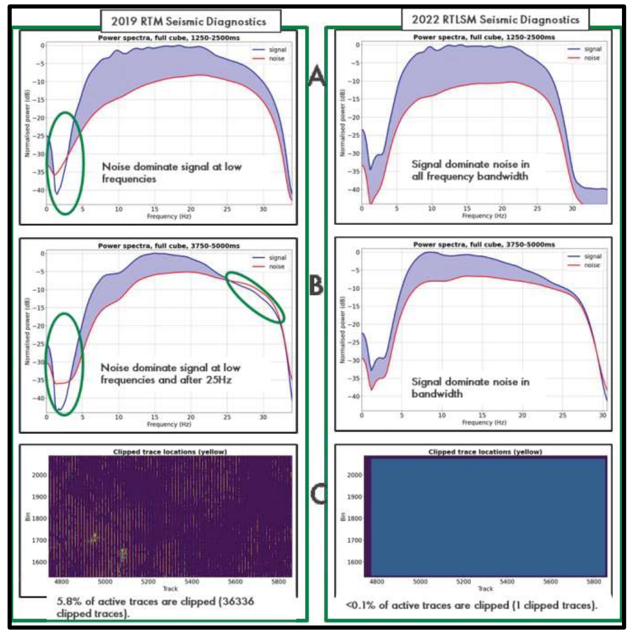

Figure 4: Seismic Diagnostic QC Plots. Plots reveal that the 2019 RTM cube has lower SNR at the lower frequency band (0 – 3Hz) compared with the RTLSM0 in the shallow (A – top plots) and deep section (B – middle plots). Overall better SNR in RTLSM cube with relatively stable amplitudes in the deep with slightly higher signal without noise corruption 27Hz. The lower plots (C) show the reduced imprint of acquisition in the RTLSM cube compared with the RTM cube in terms of visible survey outlines and clipped traces.

Pre-Stack Gathers RTLSM vs PreSDM: RTLSM pre-stack angle gathers are cleaner, with better AVA/AVO amplitude expression and alignment compared to PreSDM pre-stack gathers. The goodness of fit of the RTLSM angle gathers produced is of excellent quality and matching QI forward model of reservoirs from well synthetics. This is a very good example of RTLSM applied to onshore data with huge value creation for credible AvA work in support of the hydrocarbon maturation. Figure 5 shows these impacts.

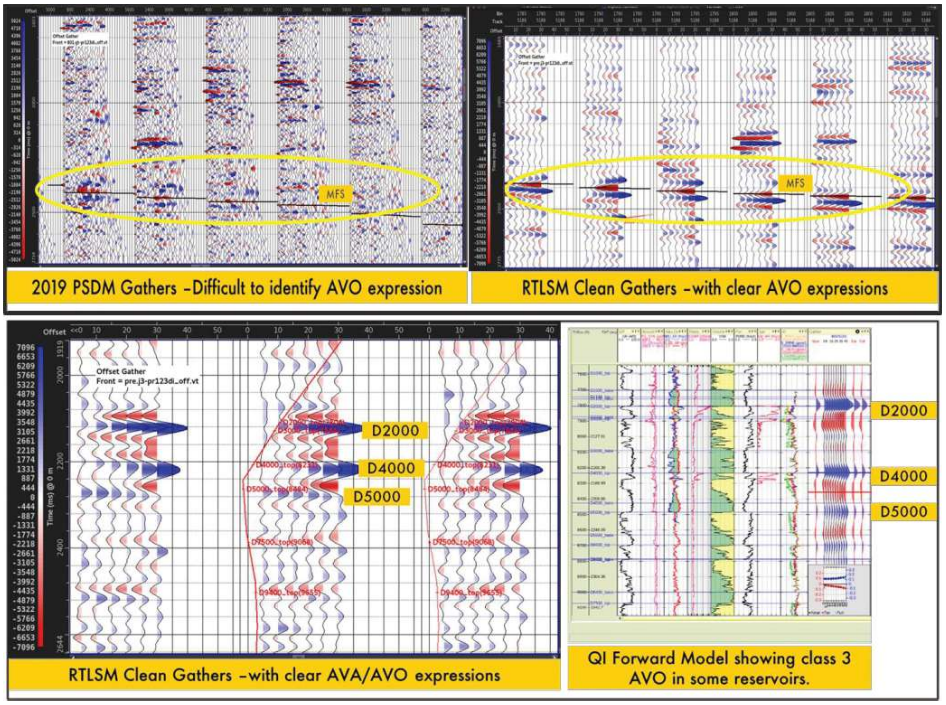

Figure 5: RTLSM Gathers cleaner with better AVA/AVO amplitude expressions compared with QI forward model (below figure) and also better aligned compared to legacy PreSDM gathers (above figure).

CONCLUSION

The RTM discussed in this paper was processed 3 year earlier. Due to limitation of time and to ensure that the new high end advanced seismic imaging solution, RTLSM is used for deep plays maturation, no velocity update model building was done. The results shown clearly confirms for this swamp case study from the Niger Delta that RTLSM technology gives better amplitudes, even continuity, better fault resolution with additional revelation of stratigraphic expressions that will help to optimize drilling campaign. The value of this work has helped to push any plan for new seismic data acquisition with its attendant high-cost implication and minimal impact on the environment to the future.

We will explore carrying out iterative RTLSM to push the resolution envelop if the cost and time of this high-end seismic imaging permits from exploration and development perspective.

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