Enhanced 4D Seismic Outcomes Through True 4D Processing – Usan Field

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Summary

The Usan field, located offshore Nigeria, has a well-established history of deriving significant value from 4D seismic analysis. The recent 2023 Monitor (M3) survey was processed alongside the baseline survey (M1) through a carefully structured, two-phase workflow.

Phase 1 focused on improving 3D data quality, leveraging historic processing flows (Agnisola *et al*., 2019) while integrating lessons learned from previous projects. Key advancements in this phase included shot-by-shot debubble, 3D sparse Tau-P inversion for precise deghosting, curvelet-based multiple subtraction, 4D regularization, and detailed velocity model building. While primarily 3D-focused, Phase 1 incorporated QC checks of 4D attributes to ensure alignment with future processing goals.

In Phase 2, the workflow transitioned to true 4D processing, implementing advanced techniques such as multi-realization binning, 4D water column correction (WCC), 4D debubble, 4D demultiple and 4D co-denoise. These comprehensive steps resulted in significant improvements in data repeatability and signal fidelity, ensuring that the processed data met the stringent requirements of 4D seismic analysis.

By integrating these advanced methodologies across both phases, the project successfully delivered high-quality 4D seismic data, providing crucial insights for effective reservoir management.

Introduction

The Usan field presents substantial imaging challenges due to its complex geological setting, characterized by a shale-cored anticline with a three-way dip closure. This environment features steep dips, radial faulting, and thin, laterally constrained turbidite channel sands, all contributing to significant lateral compartmentalization. These geological complexities demand advanced seismic processing to mitigate issues such as seismic amplitude fidelity and to enhance the resolution and repeatability of 4D seismic data.
To address these challenges and establish a strong foundation for 4D analysis, the processing workflows extended beyond standard 3D seismic tasks such as multi-domain denoising, receiver motion correction, tidal corrections, 3D water column correction, and local footprint attenuation for each vintage. The project was structured into two distinct phases, each building upon the other to progressively enhance data quality and 4D capabilities:

Phase 1 – 3D Data Enhancements

- Refinements to the existing processing sequence
- Shot-by-shot debubble
- 3D explicit deghosting
- 3D SRME with curvelet based subtraction
- 3D Full Waveform Inversion (FWI)

Phase 2 – 4D Advancements

- XOM style 4D Binning with multi-realization
- 4D WCC
- 4D Debubble
- 4D Demultiple
- 4D Co-Denoise
- 4D FWI (Davies *et al*., 2024)

These phases collectively addressed foundational improvements in 3D data quality while introducing advanced techniques tailored for effective 4D processing.

Methods and Description

In the following sections, we delve into the specific processes and methodologies applied in each phase of our 4D seismic processing project. By structuring the project into these two phases, we systematically enhanced both the quality of the initial 3D seismic data and the 4D capabilities necessary for accurate time-lapse analysis of the Usan field.

Phase 1 – Enhancing the 3D Data Quality

The success of 4D seismic processing hinges on the quality and accuracy of the preceding 3D processing. A well-executed 3D workflow is critical for creating a strong starting point for 4D analysis, but it must also be optimized with techniques tailored to enhance 4D outcomes. Poor-quality 3D processing will not yield reliable 4D results, and conversely, even excellent 3D processing alone will not guarantee high-quality 4D outputs. With this understanding, Phase 1 emphasized precise and robust 3D processing to address the complex geological challenges of the Usan field.

One of the key advancements in Phase 1 was the use of near-field hydrophone data to derive far-field signatures. This step was essential for accurate low-frequency estimation and enabled precise shot-by-shot designature (Ziolkowski *et al*., 1982), effectively mitigating shot-specific bubble noise. This process was pivotal in minimizing non-repeatable noise, a critical factor for ensuring seismic repeatability in 4D analysis.

Recognizing the significant impact of ghost-period differences on seismic repeatability and 4D metrics, we implemented explicit 3D deghosting (Wang *et al*., 2015). This method addressed the limitations of traditional 2D deghosting, which often neglects the p_y component and introduces inaccuracies in ghost delay times. By accounting for the true 3D characteristics of the data, explicit 3D deghosting ensured greater precision and repeatability. Additionally, sparse $\tau - p$ inversion was applied to tackle aliasing and enhance the resolution of weak events, especially in areas of complex geology.
Optimally removing multiples is a critical step in 4D seismic processing, as multiples often overlay the 4D signal, masking it and making interpretation challenging. To address this, we

employed curvelet domain adaptive subtraction (Herrmann *et al*., 2004), a method specifically designed to separate multiples from primary reflections effectively. The multi-resolution and directional sensitivity of curvelets enabled precise differentiation between overlapping multiples and primary signals.

This approach surpassed traditional XT adaptive methods, which often face challenges with primary signal leakage. By leveraging curvelet adaptive subtraction with carefully calibrated parameters, we ensured that primary signals were preserved while achieving confident and effective multiple attenuation. Although adaptive subtraction is typically used cautiously in 4D seismic workflows to avoid distorting the primary signal, our approach struck an optimal balance between robust multiple removal and signal preservation, significantly enhancing the clarity of the seismic data.

By meticulously implementing these processes, Phase 1 provided a high-quality and reliable input for the subsequent 4D workflow. This comprehensive preparation not only addressed the immediate challenges of 3D data quality but also set the stage for accurate and repeatable 4D seismic analysis, ultimately delivering clear and clear insights

Phase 2 – Advancing to "true" 4D processing

In Phase 2, we built upon the sail line processing framework established in Phase 1, transitioning to true 4D processing with advanced techniques designed to enhance repeatability and significantly reduce NRMS, following best practices from Christie *et al*. (2002).

In true 4D processing, the workflow begins with refining the binning strategy to ensure optimal data utilization and trace-pairs selection. A sophisticated rank-based trace selection method was introduced, employing an extended bin approach inspired by Chu *et al*. (2024). This method prioritized high-quality traces by applying a threshold criteria set on the cross-plots of ΔNRMS and the difference in source and receiver positions (DSDR), while also minimizing the rejection of trace pairs. Although the improvement over the minimum DSDR approach from Phase 1 was incremental, this strategy ensured more reliable data selection, enhancing overall repeatability.

To enhance repeatability further, the refined binning scheme was combined with an innovative approach that utilized multiple traces per offset, CMP, and vintage. This strategy enabled targeted denoising of ancillary data while preserving the integrity of the 4D signal. The outcome was a notable 2-3% reduction in NRMS, leading to a more robust and accurate 4D analysis.

Following binning, matching pursuit 4D regularization was applied to individual vintages, ensuring that diffraction tails and weak events were preserved. While time-lapse regularization techniques (Khalil *et al*., 2016) were evaluated, they yielded negligible improvements due to the already repeatable acquisition parameters. Subsequently, 4D Water Column Correction (4D WCC) was implemented to address residual cross-correlation time shift jitters. As detailed by Ong *et al*. (2015), 4D WCC is an inversion-based dynamic correction technique that simultaneously accounts for changes in water column velocity and depth. This step was critical, as uncorrected time shift jitters post-migration could obscure the true 4D signal and create migration swings, potentially masking the 4D response. Applying 4D WCC on the regularized datasets effectively mitigated these risks, resulting in a cleaner and more precise input for subsequent 4D processing prior to migration.

In all our "true 4D processing steps" (4D WCC, 4D Debubble, 4D Demultiple, 4D Denoising,) we preserve the 4D signal by selecting the highest coefficients in the curvelet domain and iteratively building upon the signal. This upfront process ensured that the true 4D signal was always kept well retained, allowing us to parameterize the processing optimally without attenuating the important signal changes.

No matter how meticulously 3D processing is performed, how efficiently time shift jitters are corrected with 4D WCC, or how advanced 4D binning techniques are applied, the 4D difference will still exhibit artifacts such as residual bubble noise, multiples, and other noise elements. These challenges necessitate dedicated and targeted methods for effective resolution.

Even with the implementation of shot-by-shot debubble correction using far-field signatures derived from near-field hydrophone data during Phase 1, residual bubble noise continued to persist in the 4D difference. These low-frequency residual bubble artifacts were likely to be due to the amplification of low frequency inconsistencies post-deghosting or mismatches left unresolved after cross-equalization. To address this challenge, we refined the debubble process using a straightforward yet effective methodology. A single debubble operator was generated for each nominal offset using gap deconvolution derived from the 4D difference. These operators were convolved with the 4D difference to accurately model bubble noises. A water-bottom flattening technique was applied to isolate bubble noise, ensuring primary reflections were preserved by removing geological influences and minimizing dip leakage. The resulting flattened bubble model was smoothened, adaptively matched, and subtracted independently from the baseline and monitor datasets, producing an updated, bubble-free 4D difference. This process not only mitigated bubble noise throughout the overburden but also ensured that the steeply dipping 4D signals in the target zone were not interfered with by overlapping bubble energy. The effectiveness of this method was validated by NRMS improvements assessed at every wavelet scale. By employing an adaptive debubble strategy, this refined methodology effectively resolved residual bubble noise, delivering a cleaner and more reliable representation of the 4D seismic signal.

Once the low-frequency residual bubbles were effectively mitigated, attention shifted to addressing mid- to high-frequency residual multiples, which persisted in the 4D difference and posed a risk of masking the true 4D signal and compromising seismic interpretation. To tackle this, a sequential workflow combining 3D residual demultiple and 4D demultiple techniques was implemented, ensuring thorough multiple attenuation. The process began with 3D residual demultiple, conducted in the common offset domain. This domain was chosen for its ability to provide a coherent geological representation and to facilitate curvelet adaptive subtraction constrained by dip masking to prevent primary leakage (Nguyen *et al*., 2017). Multiple models derived from Phase 1 SRME were 4D binned, regularized, and adaptively matched to their respective vintage datasets. This ensured precise alignment of the multiple models, effectively removing any residual multiple energy that had bypassed earlier demultiple efforts and setting the stage for the next phase. The 4D demultiple phase then targeted residual multiples in the 4D difference by adaptively matching and subtracting the 4D difference of the residual multiple models, described earlier, from the vintage's 4D difference. This approach thoroughly addressed residual multiples, preserving the integrity of the 4D signal and significantly improving seismic data quality and clarity.

The 4D co-denoise workflow is a transformative process with the potential to significantly reduce NRMS and enhance repeatability, making it an essential tool for improving 4D seismic data quality. Most industry-standard co-denoise methods focus primarily on shear leakage attenuation (Craft *et al*., 2008), our approach is also similar but updates the traditional methodology. The workflow addresses both coherent and random noise, which has the potential to create migration artifacts and compromise the 4D signal. Iterative 4D denoising techniques are employed to mitigate these effects, ensuring improved data clarity and signal fidelity. This process leverages curvelet coefficient matching techniques to isolate and reduce noise in the 4D difference between the baseline and monitor datasets. The process begins by computing the initial 4D difference, ensuring signal preservation mechanisms are active to maintain the integrity of the true 4D signal. Noise components are isolated by scaling the curvelet amplitude coefficients of the 4D noise to a user-defined threshold relative to the baseline. This noise model is adaptively matched to the monitor dataset and subtracted, effectively reducing noise. The 4D difference is then updated, and the process is reversed. Using the refined monitor dataset, the updated 4D difference is scaled to the monitor's user-defined threshold. The resulting noise model is matched and subtracted from the baseline dataset. This bidirectional approach—first baseline to monitor, then monitor to baseline—iteratively refines the noise model, significantly reducing non-repeatable noise in both datasets while preserving the true 4D signal. To further enhance results, a final step specifically targets random noise. A 4D random noise attenuation pass applies 3D adaptive Cadzow filtering to isolate coherent signals from the 4D difference and attenuate residual random noise. This ensures even subtle, non-repeatable noise components are minimized. By combining coherent noise removal with random noise attenuation, this robust workflow achieves substantial NRMS reductions while preserving the integrity of the 4D signal, resulting in high-quality, reliable seismic data for precise and clear interpretation.

The impact of true 4D processing on NRMS (computed on the raw migrated volumes from Phase 1 and Phase 2) was substantial across all zones. In the overburden, NRMS improved by 5–6%, while the target zone saw reductions of nearly 9-10%. The most dramatic improvement occurred in the deeper below-reservoir zone, with a reduction of approximately 15-16%

These outcomes highlight the success of the comprehensive 'true' 4D workflows, which collectively produced a much cleaner and more interpretable 4D seismic dataset. Tailored to the geological intricacies of the Usan field, Phase 2 processing achieved seismic data with enhanced repeatability and improved signal clarity. This accomplishment underscores the vital role of true 4D processing in ensuring accurate seismic interpretations and facilitating effective reservoir management strategies.

Results

The offset-class time slices of the 4D differences were specifically selected to illustrate the effectiveness of true 4D processing across the entire survey area and offset classes, highlighting the improvements in S/N ratio.
Figures **1a** and **1b**: Time slices of the 4D difference (Offsets 350m and 2200m, respectively) at the reservoir level after Phase 1 processing reveal substantial random noise and artifacts, including time shift jitters, multiples, bubbles, and residual noise, which obscure the clarity of the 4D signal.
Figures **2a** and **2b**: Time slices of the 4D difference (Offsets 350m and 2200m, respectively) following Phase 2 processing demonstrate significant improvements achieved through advanced 4D techniques. Noise and non-repeatable components are effectively attenuated, allowing the 4D signal to emerge much more clearly.
The NRMS (computed on the raw migrated 3D stack volumes from Phase 1 and Phase 2) illustrates the improvements achieved through Phase 2 processing: Figures **2a**, **2b**, **2c**: Represent NRMS values from Phase 1, revealing higher levels of non-repeatable noise in the shallow or overburden, target or reservoir level, and deeper or below reservoir level windows. Figures **3a**, **3b**, **3c**: Correspond to Phase 2 NRMS values, demonstrating significant reductions in noise across all windows.
These improvements showcasing the transformative impact of true 4D processing.

Conclusions

In our comprehensive seismic processing workflow, we started with 3D data enhancements in Phase 1. Moving into Phase 2, we transitioned to true 4D processing, emphasizing precise 4D binning, 4D WCC, 4D debubble, 4D demultiple, and 4D cooperative denoising. These advanced techniques significantly improved data repeatability and reduced NRMS, ensuring high-quality, reliable 4D seismic data. By integrating these methods, we captured subsurface changes with exceptional precision, providing valuable insights that are crucial for effective and ongoing reservoir management.

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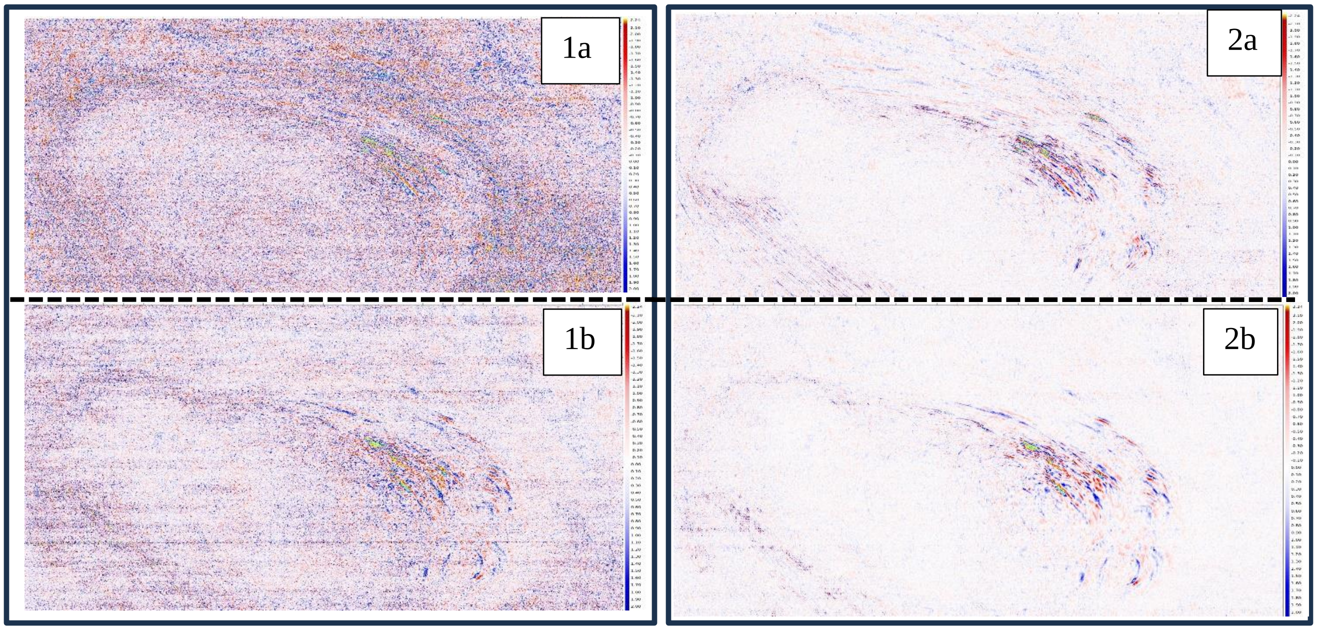
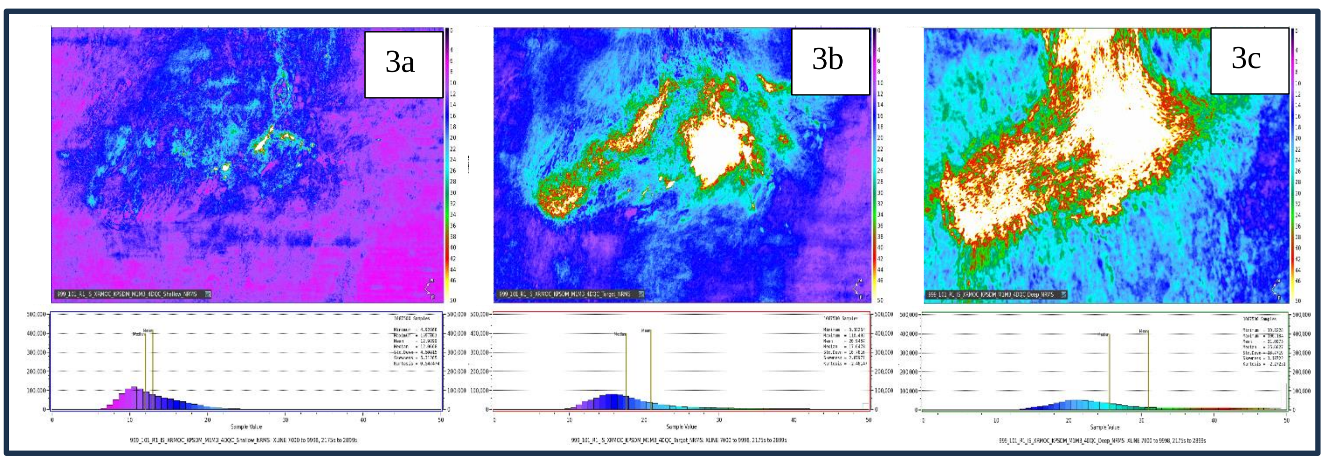


Figure 1a, 1b: Time slices of the 4D difference (Pre-migration, offsets 350m and 2200m, respectively) at the reservoir level after Phase 1 processing.
Figure 2a, 2b: Time slices of the 4D difference (Pre-migration, offsets 350m and 2200m, respectively) at the reservoir level after Phase 2 processing.



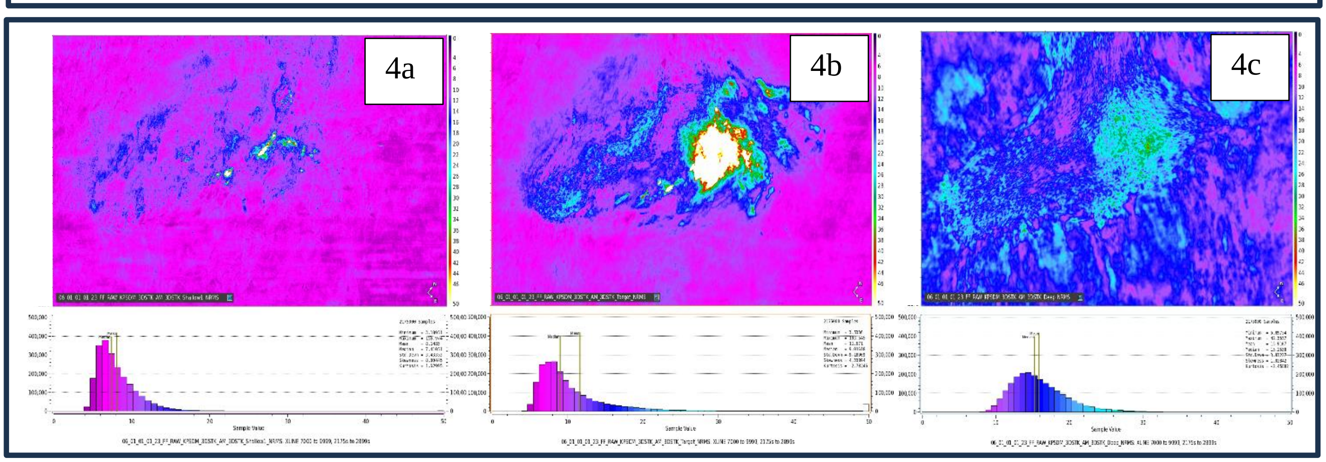


Figure 3a, 3b & 3c) Shallow, Target and Deep Window NRMS* of Phase 1 (Mean NRMS from left to right: ~13%, ~21%, ~31%).
Figure 4a, 4b & 4c) Shallow, Target and Deep Window NRMS* of Phase 2 (Mean NRMS from left to right: ~08%, ~12%, ~16%)

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