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Enhanced Full-Azimuth Q-PreSDM Imaging, Onshore Colombia – Resolving Absorption, Leveraging Rich Azimuths and Implementing Diffraction Imaging

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Summary

Optimized time-domain pre-migration reprocessing and advanced full-azimuth (FAZ) depth imaging of a 3D rich-azimuth land seismic dataset from the mature Middle Magdalena Valley Basin, onshore Colombia, resulted in a step-change in pre-stack time and depth migrated image quality and resolution, without the need for excessive post-migration processing and amplitude gains, and reliably tied to well logs at Eocene reservoir level. We present a case study in which successful deployment of new-generation processing and imaging techniques, QC processes and advanced depth migration algorithms with Q-compensation was carefully integrated to achieve all imaging and exploration goals. High-frequency absorption was not even reported nor resolved in any legacy processing passes, which illustrates that imaging challenges need to be identified before geophysical solutions can be planned and implemented. Strong Quality Control is vital. The enhanced reflection PSDM image was complemented by depth-domain dip-angle diffraction imaging, adding value to fault characterization in conventional and unconventional (Cretaceous) target intervals. The obtained results provide geologists and interpreters with insight into the Eocene reservoir in the Middle Magdalena Valley, Colombia. Diffraction imaging, applied onshore, is capable to show details otherwise considered sub-seismic, related to small faults, fractured zones, and other subtle seismic features.

Introduction

To ensure that planned reprocessing of vintage onshore seismic datasets, from field shots to migrated products, provides *true* value to all end-users of pre- and post-stack seismic deliverables relative to any legacy benchmark volume(s), at least a different strategy and differentiating technologies and solutions are to be deployed with respect to all previous processing work. Merely “reprocessing for the sake of reprocessing”, *i.e.* using a very similar or commoditized land seismic processing sequence (albeit with different seismic service providers or teams) seldom yields the required step-change improvement in image quality or a significant reduction of geological uncertainty, or worse. This is particularly true in onshore areas where available 2D/ 3D seismic programs cover a relatively non-complex geology, and have been repeatedly reprocessed by various seismic vendors to a point where decision-makers, asset managers, interpreters, geologists, drillers, inversion specialists, end-users and other key stakeholders have reached consensus that the seismic image quality cannot be improved further. With this case study we argue that, before new seismic data acquisition programs are considered and designed, all significant signal, imaging and noise challenges are identified, fully understood, quantified and subsequently addressed/ resolved by a high-end time-domain pre-migration reprocessing sequence. In addition, this enhanced reprocessing and imaging sequence should always include evaluation and optimization of anisotropic (tomographic) depth imaging, high-resolution near-surface and overburden model building, Kirchhoff and alternative advanced Pre-stack Depth Migration (PreSDM) algorithms and all new-generation onshore seismic processing capabilities.

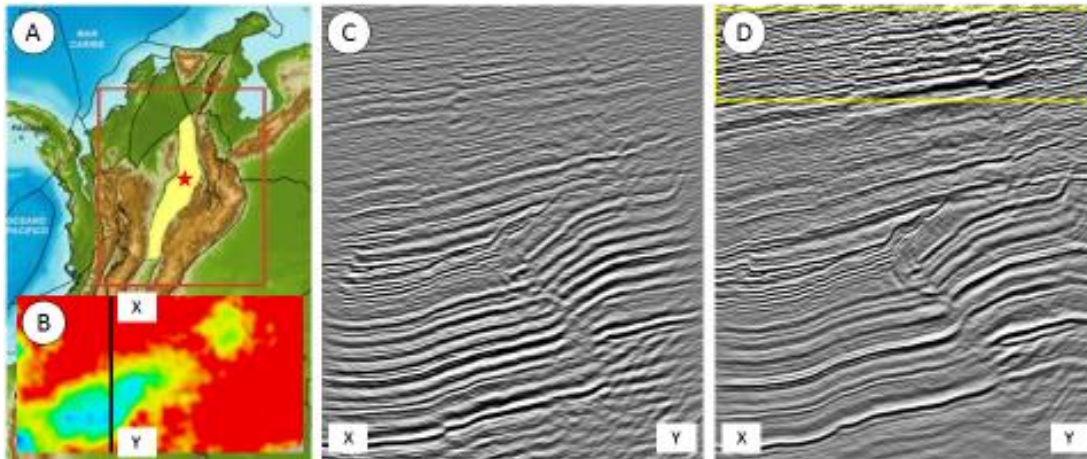


Figure 1 a) Location of the Middle Magdalena Valley (VMM) basin, and study area herein; b) Dominant frequency map of a reprocessed stack (0.5-1.0s window, yellow); c) Legacy ISO KPreSTM stack (enhanced, AGC); d) Reprocessed VTI PreSDM stack (in time, raw, no AGC). Vertical axis: 500-4000ms.

Here, the relatively small areal size of the 3D seismic survey reprocessed in this case study provided opportunities to test and benchmark, against the best-to-date, legacy Kirchhoff PreSTM (enhanced) stack volume, a range of raw and enhanced 2019 reprocessed and migrated stacked images:

- **Isotropic Kirchhoff PreSTM**, to show the value added by an optimized pre-migration sequence.
- **Anisotropic VTI Kirchhoff PreSDM**, in time/ depth, to show the benefits of Kirchhoff PreSDM, with high-resolution VTI anisotropic V_p models from full-azimuth reflection tomography.
- **FAZ Anisotropic VTI Q-PreSDM**, in time and depth, to show added value of Q-compensation within PreSDM, obtaining full-azimuth PSDM CIP gathers, and using advanced PSDM algorithms.
- **FAZ VTI PSDM Diffraction Imaging**, in depth, show the added value of Diffraction Imaging.

This small 3D seismic survey is located in the Middle Magdalena Valley (VMM) basin, onshore Colombia, and covers a monocline Tertiary overburden, the Eocene basal sandstone reservoir interval (La Paz Fm.), which in turn on-laps a prominent Eocene angular unconformity truncating the Cretaceous interval (Figure 1). The main structural features in this Cretaceous section, in which the La Luna and Tablazo formations constitute prolific source rocks and unconventional reservoir targets, are associated with positive flower structure (pop-up) and a regional dextral strike-slip fault.

Processing & Imaging Sequence

Extensive non-standard 3-pass surface-consistent (SC) amplitude corrections, *including* a pass of SC ground-roll amplitude gain, and a 2-window SC (spiking) deconvolution pass were applied in order to produce final migrated (post-stack) volumes that did not require any Automatic Gain Control (AGC) or aggressive amplitude balancing techniques. In the legacy PSTM stack volume, and typically, short-window AGC diminishes relative amplitude relationships, both vertically and laterally, even post-stack.

Moreover, a new-generation Integrated Near-surface Characterization (INSC) method was deployed throughout the reprocessing project, following Wiarda *et al* (2019), in order to aid the QA/QC and decision-making processes for *all* SC processes, to reduce project turn-around, and to identify and understand signal and noise challenges very early in the sequence. As a result, remedial processes were planned and executed as early as possible. Specifically, INSC was used throughout pre-migration time processing to *a)* identify in earliest processing some severe high-frequency absorption problems; *b)* quantify the extent of these absorption issues and produce polygons that delineate the observed high-frequency absorption effects, and *c)* provide strong correlation/ evidence that this high-frequency absorption is associated with only the near-surface zone. Since “constrained” Q-tomography solutions were unfortunately outside of project scope, and not feasible due to time and expected signal-to-noise ratio (SNR) limitations, these INSC polygons were paramount in generating the Q model input into final Q-PreSDM production. Figures 1b and 2 illustrate the final Q-anomaly geobody resulting from scanning low Q values, populating the shallow absorption polygon, as well as testing smooth geobody boundaries and layer thickness that optimally resolved this near-surface absorption in Q-PreSDM (*i.e.* amplitude-phase Q-compensation *within* PreSDM). This implementation of the final Q model with shallow absorption anomaly for Q-compensation inside Q-PreSDM (Podolak *et al.*, 2016) proved to be a superior, more sophisticated and effective solution of improving laterally wavelet stability than any equivalent *post-migration* Q-compensation (*i.e.* tested *after* Kirchhoff PreSTM and PreSDM) using similar Q-models with anomalously low-Q geobodies in the near-surface polygonal zone (figure 2).

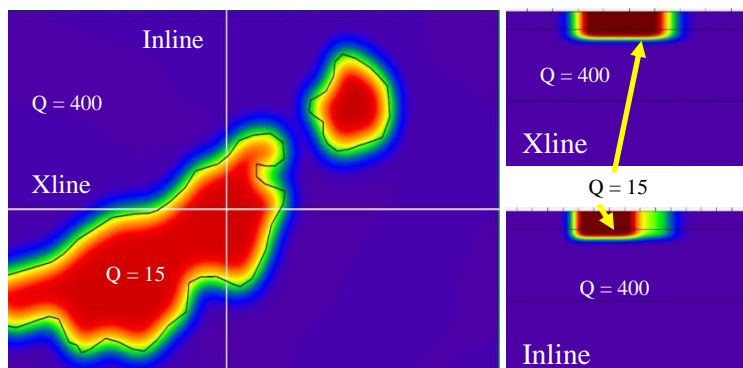


Figure 2. Horizontal and vertical sections of the Q model applied to compensate for the local anomaly of the emitted wavelet shape.

To mitigate the risk of any unresolved high-frequency absorption effects across the 3D survey area of interest, and to adhere to industry best practices and seismic pre-stack inversion data requirements, strong emphasis was placed on preserving

low-frequency content and enhancing *low-frequency SNR* throughout the pre-migration sequence and post-migration processing. In this effort, ground roll removal with a local Singular-Value Decomposition technique, followed by hybrid multi-domain (source, receiver, CDP, cross-spread) noise attenuation, both with signal protection and add-back, proved very effective.

Due to a relatively wide source and receiver line spacing, and given the number of active receiver lines per shot, the 3D seismic survey used in this study exhibits a nearly square (1:1) inline-crossline acquisition patch and therefore a rich azimuth distribution relative to other 3D seismic surveys in the central VMM basin. Therefore, a key aim of the recent reprocessing and depth imaging project was to leverage this relatively rich azimuth distribution by preserving these azimuths through regularization/ interpolation, by defining appropriate offset-vector tiles, by full-azimuth (FAZ) tomographic velocity model updates, and by final FAZ local angle-domain Q-PreSDM production (Kowalski *et al.*, 2014).

Finally, Diffraction Imaging was implemented in depth domain (*e.g.* Moser *et al*, 2020) in order to support the characterization of subtle small-scale fault trends in the conventional Eocene reservoir and unconventional Cretaceous intervals, by splitting the input wave field into complementary components:

specular and diffraction. Key steps of the depth imaging phase included 1) isotropic initial V_P model building (incorporating the shallow refraction tomography model); 2) conventional single-azimuth, multi-scale tomographic inversion, with four V_P model updates with focus on Tertiary overburden and near-surface zones; 3) conversion to VTI anisotropic V_P model - Anisotropic VTI Thompson's delta field estimation by minimizing well-seismic mis-ties ($Epsilon = 1.5x \Delta$), and finally 4) iterative, full-azimuth tomography. All aforementioned Kirchhoff and Pre-stack Depth Migration algorithms, including for Diffraction Imaging, were run in production with the same input data and VTI anisotropic interval V_P PSDM model.

Results

Figure 1 shows a compelling benchmark comparison between the post-processed migrated stack volumes of the legacy (isotropic) Kirchhoff Pre-stack Time Migration (ISO KPreSTM), figure 1c), and the (anisotropic VTI) Pre-stack Depth Migration (VTI KPreSDM), converted to two-way time (Figure 1d). The unambiguous (cumulative) image-quality improvement caused by the integration of *all* the aforementioned time-domain pre-migration techniques, the anisotropic and full-azimuth tomographic depth imaging model enhancement and more sophisticated depth migration algorithms has added significant value in terms of geological uncertainty reduction. Beyond the conventional Kirchhoff PreSDM algorithm, the final FAZ local angle-domain Q-PreSDM image volume provided full-azimuth directional gathers for future azimuthal anisotropy analysis, and high-quality vertical sections (figure 3) with local shallow absorption issues (partially) resolved.

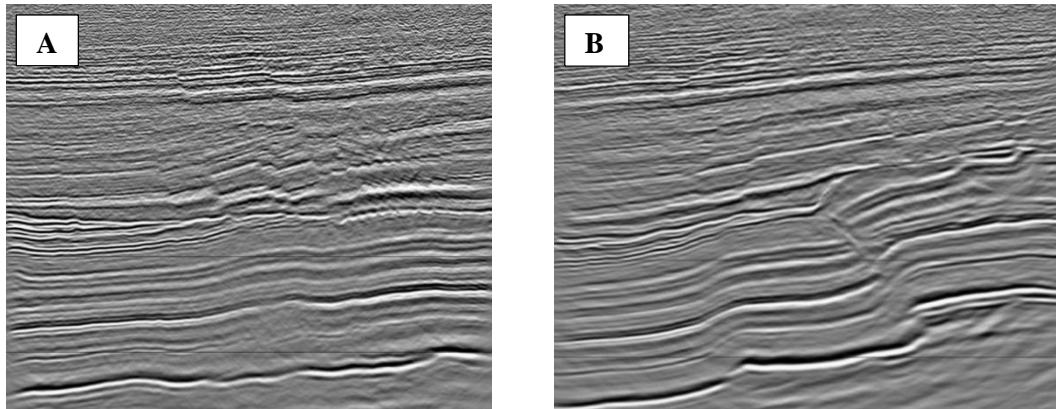


Figure 3. FAZ Q-PreSDM stack section of: a) inline (fig. 4a, horizontal line); b) cross-line (fig. 4a, vertical)

A sample result of the obtained Diffraction Image depth volume is shown in figure 4b. Figure 4 provides a depth-slice comparison near the Eocene Unconformity within the survey polygon of a) classical reflection image, with the b) diffraction component of the same input seismic data migrated with the same VTI interval V_P model. Figure 5 shows a zoom-in subset of the directional (full reflection) VTI Q-FAZ PreSDM stack sections of figure 3, with the VTI FAZ PreSDM Diffraction Image stack sections co-blended. Note in figures 4 and 5 the correlation and complementary value of information that the enhanced diffraction imaging volume brings relative to the associated reflection depth image in both depth slices and vertical sections (again, using same input to migration and migration velocity models).

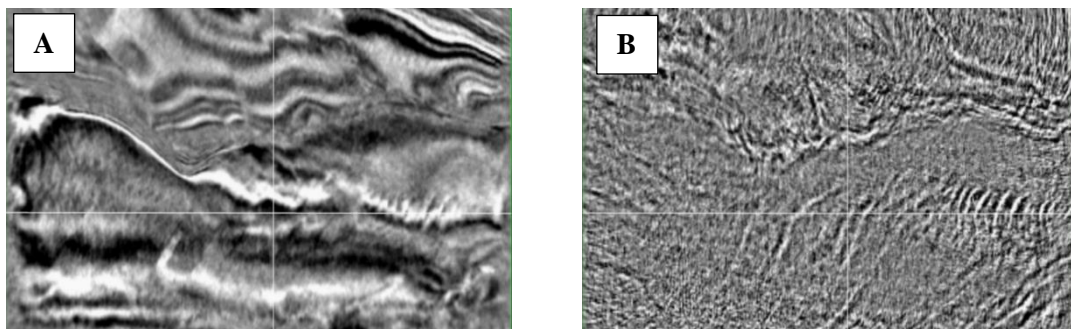


Figure 4. Depth slice near the Eocene Unconformity in the VMM 3D survey polygon, observable in figure 3, of a) the "conventional" reflection VTI PreSDM CDP stack volume and b) of the Diffraction Imaging cube (raw CDP stack of diffraction gathers).

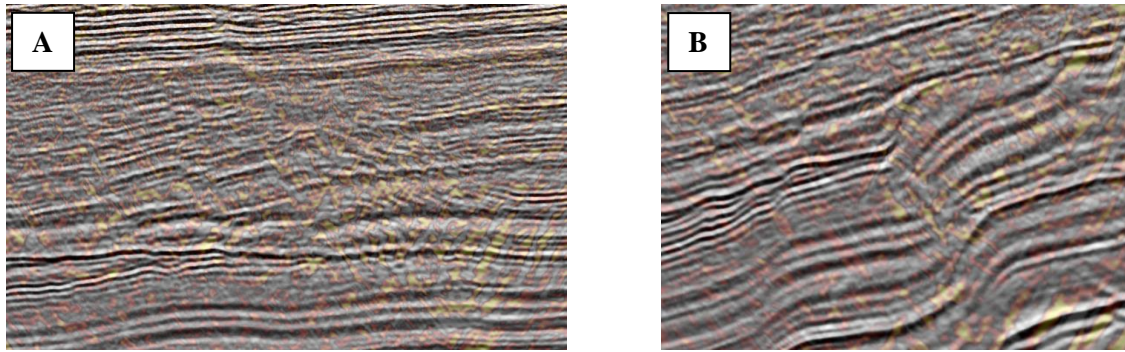


Figure 5. Zoom-in subsets of the directional (full reflection) VTI Q-FAZ PreSDM stack sections of figure 3, with the VTI FAZ PreSDM Diffraction Image stack sections co-blended for a) strike line through minor echelon strike-slip faults near a major Cretaceous wrench fault; b) dip line perpendicular to this eroded Cretaceous positive flower (pop-up) structure.

Conclusions

Benchmarking with the best-to-date legacy Kirchhoff PreSTM stack volume reveals that the reprocessed KPreSTM volumes bring value to the table, in terms of reflection continuity, fault definition, SNR, bandwidth at low- and high-frequency ends, lateral and vertical resolution, wavelet amplitude and phase stability, (migration) artefacts and false structure. This incremental value can be attributed to the implementation of a new optimized pre-migration processing sequence. Leveraging the rich azimuth distribution from the acquisition geometry of the 3D survey used in this case study provided a high-resolution FAZ tomography V_P model for all final PSDM algorithms and directional FAZ PSDM gathers for future azimuthal (anisotropy) analysis. INSC-driven Q-model building in the near surface provided a stronger solution when used implicitly inside the final Q-PSDM. High-frequency absorption was not even identified nor resolved in any legacy processing passes. In addition, we discuss the image-domain implementation of Diffraction Imaging with a focus on the Eocene reservoir and Cretaceous intervals, a relatively new method of imaging subtle subsurface discontinuities *e.g.* fractured zones, fault edges, small-scale faults, pinch outs, angular unconformities, and other scattering objects below typical seismic resolution limits. Diffraction Imaging is considered in this study as a complementary product to the structural images produced by reflection imaging. With diffraction imaging techniques, new seismic insight into the subsurface is available to geologists. Fault patterns can now be interpreted from Tertiary overburden, through Eocene reservoir, and connected to Cretaceous wrench faults into the basement.

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