Introduction

Along with the improvements in seismic noise attenuation technologies and increased industry experience with onshore seismic data, reprocessing legacy surveys grew in significance, also due to the reduction of exploration budgets. In these cases, a key aspect of seismic processing is committed to data enhancement routines, focusing on reconstructing the reflection from the signal acquired through legacy technology while, for optimal noise attenuation, there is rising demand for algorithms capable of operating on geometries sparser than modern surveys. Herein, advanced seismic processing techniques are presented on a case study onshore Colombia, where two overlapping 3D surveys were merged as part of a time reprocessing and depth imaging sequence.

Geological setting

Bounded by the Eastern and Central Cordilleras of the Colombian Andes, the Middle Magdalena Valley Basin is located along the central reaches of the Magdalena River valley, and constitutes a deep Cenozoic intermontane sedimentary basin. Structural development took place through three different phases, linked to South American tectonic events occurring between the Late Triassic and Middle Neogene. Jurassic continental deposits overlain by Cretaceous sediments, both calcareous and siliciclastic, of transitional to marine origin comprise the sedimentary record. The Paleogene sequence consists mainly of continental siliciclastic rocks, with some marine influence. The area of interest covers approximately 300 km² across La Salina, Corazon, and Payoa-Provincia fields. The producing depths extend from less than 300 m to 4000 m, with reservoirs being highly faulted and folded Tertiary sandstones. Hence, structural delineation and accurate spatial positioning of faults and unconformities are primary objectives of recent 3D time and depth reprocessing programs. The structural complexity across the study area is illustrated in Figure 1.

Figure 1 Simplified W-E cross section and structural map over the study area (red polygons), and stratigraphic column. The area is characterized by a high degree of folding and faulting.

Seismic challenges and solutions

The two 3D seismic surveys input to the merge were characterized by a complex acquisition layout due to slanted spread geometries and variations in the nominal acquisition pattern, both inter- and intra-survey (infill). Moreover, the actual source and detector spacing was affected by presence of roads and infrastructures. The overall non-uniform sampling strongly limits the applicability of conventional dip filtering workflows.

The data set complexity was further increased due to overwhelming contamination by noise. In addition to the random noise, common to any land survey, the data set was severely affected by environmental noise generated by neighbouring infrastructures such as roads and production facilities. Nevertheless, the most complex challenge was the scattered and aliased ground roll, as illustrated in Figure 2. The attenuation of this complex surface-wave noise was approached based on surface-wave analysis and modelling (Strobbia et al., 2011) and non-uniform coherent noise suppression.
To achieve seamless imaging of the volume of interest, the input surveys were matched in amplitude and phase and reconstructed on a regular grid by means of 5D matching pursuit Fourier interpolation (Schonewille et al., 2013). As a result of its reconstruction capabilities and excellent amplitude preservations, the matching pursuit approach was found to be also one of the most effective solutions for enhancing the signal with respect to the noise and to improve the reflection focusing; this workflow was implemented both in the pre- and in the post-migration domain, leveraging different interpolation axes.

Finally, the structural complexity of the area required transverse tilted isotropy (TTI) anisotropic prestack depth migration and tomographic velocity model building to ensure structural delineation and accurate spatial positioning of faults and unconformities.

### Noise attenuation and broadband signal processing

Among the various noise characteristics present within the data, random noise bursts and anthropogenic noise were effectively addressed following industry-standard approaches based on median filtering and amplitude discrimination in the frequency domain. Conversely, source-generated noise, the so-called ground roll, required a tailored approach. Characterizing the dispersive propagation of Rayleigh waves enabled modelling and subtraction of those high-energy events that shadow the reflection data. Differently from conventional dip filtering, this process can correctly model the spatially aliased events occurring due to the fairly large source and receiver spacing of the surveys.

A cascaded application allowed for resolving the ground roll propagation into separate phase velocity modes. The method was not constrained by the assumption that the surface wave is ‘direct’ from source to receiver, but it modelled also surface-wave energy originated from scattering bodies. After having addressed the dispersive modes, the remnant linear noise was removed by non-uniform coherent noise suppression, which estimates multiple bands of coherent noise at each location by means of frequency-space (f-x) domain fan filters and a least-squares optimization scheme. The workflow devised successfully handled non-uniform spatially sampled seismic data, as well as (back-)scattering and aliased ground roll. Figure 3 represents a shot gather selection before and after the ground-roll attenuation sequence, illustrating the excellent noise removal capabilities.
Figure 3 Shot gather A) before, and B) after the coherent noise attenuation sequence, which successfully attenuates most of the direct, scattered (arrows) and aliased ground roll uncovering the primary reflections. Remnant noise will be addressed at later stages with matching pursuit techniques.

Matching pursuit Fourier interpolation techniques are used not only for multi-dimensional interpolation and regularization of sparsely and irregularly sampled data, but also to improve the signal-to-noise ratio by iteratively modelling the seismic data in a domain where signal and noise can be easily and effectively separated. This provides optimal removal of random noise and improves continuity of coherent events.

This approach is particularly effective when applied in conjunction with a robust surface-consistent deconvolution (Hootman, 2011), whose solver is capable of detecting and weighting down outliers during decomposition. This overcomes the limitations of conventional surface-consistent deconvolution methods, which would underperform in presence of residual noise, such as remnant ground roll or ambient noise bursts that are not surface consistent. Such noise would have contaminated the surface-consistent decomposition and biased the operators affecting their stability.

Applying matching pursuit noise attenuation and robust deconvolution, and the subsequent 5D interpolation, optimized the data quality input to prestack time and prestack depth Kirchhoff imaging. Figure 4 compares the legacy and the reprocessed data sets after prestack time migration and post-processing: the uplift achieved in resolution, reflection continuity, and overall imaging is remarkable.

Figure 4 Kirchhoff prestack time migration comparison between, A) the two legacy, and B) the merged and reprocessed volume. On the former, the seam between the two volumes is apparent; the latter benefits from broader frequency content and improved continuity and imaging quality.

From time to depth imaging

Reduction in structural uncertainty was one of the key objectives of the reprocessing and imaging. Delineating trap geometries is crucial in this environment, thus improvements in fault imaging were pursued to reduce uncertainty in fault-plane angle and vertical extent. To achieve that and overcome the intrinsic limitations of time imaging, TTI depth imaging was mandatory for the case study.
The definition of the optimal initial model is paramount to ensure smooth convergency of the linearized tomography iterations. This was achieved by leveraging spatially continuous velocity analysis and structural smoothing, starting from the time imaging velocity and dip field. The automated, data-driven approach was both accurate (see well-log extraction in Figure 5A) and time-effective, leading to a high-resolution, geologically-consistent model, an ideal starting point for reflection tomography. At the time of writing, initial isotropic updates, prerequisite to the anisotropy characterization, are complete (Figure 5C), and the subsequent tomography iterations will lead to the final depth imaging product.

Conclusions

Revisiting the signal processing and imaging strategy has added value in the pursuit of local exploration and development objectives by significantly improving the signal-to-noise ratio and resolution of the seismic volume. The cascade of surface wave and matching pursuit noise attenuation, coupled with anisotropic depth imaging, reduced the structural uncertainty. Additionally, prestack merging of the velocity models and legacy seismic data sets are significant steps towards accurate structural imaging in and around the overlap area of the surveys. This case study demonstrated the possibility of achieving significant improvements to structurally complex legacy data sets by applying a contemporary processing sequence.

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References

