Azimuthal Inversion Applied to a Fracture Characterization Study: A Pre-salt Case Study, Brazil.

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Summary

In recent years, the Brazilian presalt characterization has been a challenging task, either because of the imaging problems associated with complex salt layer geometry (Penna et al., 2019) or due to large heterogeneity in the presalt carbonates reservoir (Oliveira et al., 2018). Some efforts to address these challenges include full-azimuthal acquisitions technologies (nodes acquisition) and new processing techniques and studies to better understanding the geological model. Recent multi-azimuthal seismic data acquisition provides not only better seismic imaging, but also fractures properties through velocity and amplitude changes with azimuth variation, providing a better spatial characterization of the fracture system. We present an azimuthal elastic seismic inversion (Roure et al., 2012) in a Nodes presalt reservoir data, addressing the local fracture system characterization. Fracture parameters are described in terms of the normal and tangential weakness plus fracture strike. Prior to the inversion, an azimuthal seismic preconditioning has also performed on the seismic dataset to attenuate the imaging problems in the reservoir interval and consequently improving the signal-to-noise ratio providing better estimates of the properties of interest.

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In recent years, the Brazilian pre-salt characterization has been a challenging task, either because of the seismic imaging problems associated with complex salt layer geometry (Penna et al., 2019) or due to large heterogeneity in pre-salt carbonate reservoirs (Oliveira et al., 2018). Efforts to address these challenges include full-azimuth acquisition technologies (e.g., node acquisition), advanced processing techniques, and studies to better understand the geological context.

Most of the studies addressing pre-salt reservoirs are focused on different pre-salt lithofacies discrimination, generally based on sedimentary matrix features and its elastic properties derived through elastic seismic inversion (Oliveira et al., 2018; Kneller et al., 2019). However, it is well-known that the Brazilian pre-salt reservoir presents high average production rates consistent with the presence of non-matrix features in carbonates (Fernandez-Ibanez et al., 2020), and by the presence of fractures networks, confirmed by wells drilled in Santos and Campos basins (Wennberg et al., 2020). Therefore, fracture influence studies are essential for better reservoir planning and management, particularly in the light of the new azimuthal data available for the Brazilian pre-salt.

Fracture characterization studies commonly integrate borehole image logs, core data, and well tests, usually restricted to specific areas around drilled wells. In some cases, tridimensional fracture models are created through geostatistical modelling constrained by seismic attributes. However, those are indirect measures of fractures, with high associated uncertainties. Recent multi-azimuthal seismic data acquisition provides not only better seismic imaging, but also anisotropic information through velocity and amplitude changes with azimuth variation, allowing a better spatial characterization of the fracture system.

In this study, we present an azimuthal elastic seismic inversion (Roure et al., 2012) applied in a multi-azimuthal seismic dataset from node acquisition, addressing the local fracture system characterization. Fracture parameters are described in terms of the normal and tangential weakness plus fracture strike. Prior to the inversion, an azimuthal seismic preconditioning was also performed to improve the signal-to-noise ratio and the accuracy of the seismic amplitudes, providing a better quantitative estimation of the reservoir properties.

Seismic Preconditioning

One of the key roles in the seismic reservoir characterization study is evaluating the data quality and trying to improve the signal-to-noise at the reservoir target as much as possible. Thus, prior to the azimuthal inversion, a seismic preconditioning workflow, as proposed by (Oliveira et al. 2018), was applied on the seismic data. An accurate quality control (QC) was performed, in order to monitor seismic amplitude accuracy, AVO response preservation, and data quality improvements along the processing sequence.

Three preconditioning steps in the pre-stack domain were applied on the 12 azimuthal seismic sectors and consisted of incident angle muting, F-X domain projective filtering, and range stacks definition. The projective filter was able to attenuate most of the high-frequency noise present in the near angles, improving the lateral continuity of seismic events. We considered the best angle stack range that better fits the AVAz/AVO curve through average angles.

In the post-stack domain, we performed a Q inverse and structurally consistent filtering, as well as partial stack time misalignment corrections. The inverse Q filter compensates the amplitude absorption effects providing a better vertical resolution in the reservoir. The structurally consistent filtering attenuates coherent noise generated by salt flanks. Lastly, a time misalignment correction was applied to remove residual misalignment among azimuthal angle stacks.

At each preconditioning step, we performed an accurate quality control, guaranteeing the seismic data improvement after each stage.

A comparison of RMS amplitude and signal-noise ratio (SNR) maps at the reservoir interval is shown before and after preconditioning in Figure 1. Observe the data quality improvement with a higher signal-noise ratio as shown in the map and their respective histograms. These improvements are first order in stabilizing the anisotropic gradient computed from the data through Ruger azimuthal inversion, as shown in Figure 2. After preconditioning, the lateral continuity is strongly enhanced, and the resolution appears slightly better in some parts of the reservoir.

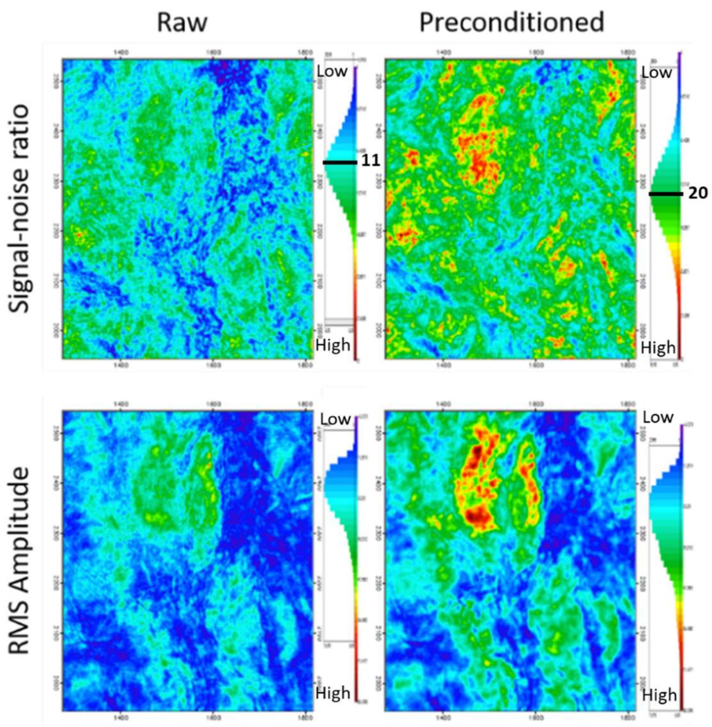

Figure 1: Signal-to-noise ratio (SNR) and RMS maps before and after seismic data preconditioning.

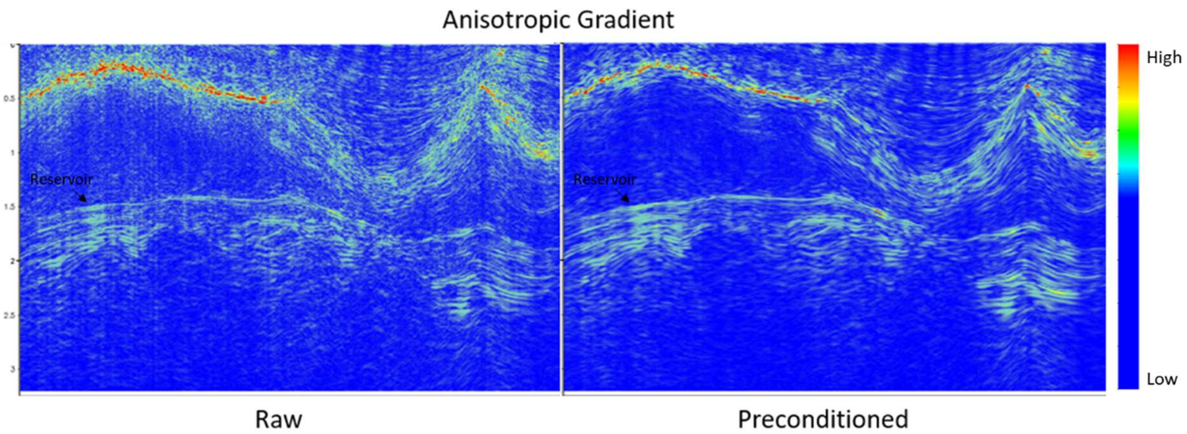

Figure 2: Comparison between anisotropic gradient obtained through Ruger azimuthal inversion using raw and preconditioned data as input.

Azimuthal Fourier Coefficient Elastic Inversion

The azimuthal Fourier Coefficients transform (FC) is an alternative method to analyse the data for fracture properties estimation, as demonstrated by Downton et al. (2011). For each angle of incidence, the AVAz signal can be decomposed into FCs that can be used individually or in combination to make inferences about the anisotropy and fractures. Considering a linearized expression of the azimuthal reflectivity and assuming the reciprocity of the PP seismic data, most of the azimuthal information is contained in the 2nd order cosine (u_2) and sine (v_2) terms and the 4th order cosine (u_4) and sine (v_4) terms.

Roure et al. (2012) proposes a model-based approach where these azimuthal FC terms, derived from the azimuthal angle stacks, are inverted to estimate fracture properties. This methodology assumes a weak HTI anisotropic media due to a single set of vertical fractures, which can be parameterized in terms of weakness through the linear slip theory. The inverse problem is solved using a simulated annealing technique to minimize a three-term cost function. The first term corresponds to the misfit between the real data and the modelled data calculated by the convolution of the reflectivity using FCs and angle dependent wavelets. The second term measures the distance between the prior and current models and controls how far the solution is allowed to move away from the initial trend. The third term controls the lateral continuity of the estimated parameters, proportioning smoothness and stability to the results.

The azimuthal inversion from FCs was applied on the preconditioned azimuthal seismic data. Anisotropic properties such as fracture density and isotropy plane are generated by azimuthal inversion. These data are illustrated in mean stratigraphic reservoir interval maps as shown in Figure 3.
In the fracture density map (Figure 3, left), yellow-to-red colours represent high fracture density values and are mainly concentrated at the western boundary of the field. The isotropy plane vector map (Figure 3, right) denoting the fracture direction, shows a preferred SE-NNW direction in the western limit towards the yellow well. This structural direction is corroborated with regional faults studies, as illustrated by Carlotto et al. (2017).

These results are also compared with some reservoir engineering data available in Figure 4. According to the data, a great loss of fluid circulation during well drilling has been noticed at this western limit, probably due to the high fracturing level in this area. Furthermore, the western well (yellow circle in Figure 3) is one of the best producing wells in this area, potentially due to the large presence of aligned fractures in the SE-NW direction.
Note that circulation loss is not necessarily associated with a high fracture level predicted by seismic data (south well), because this event may be associated with other factors such as rubble zones at the interface between the salt and other rocks that act as flow conduits, in addition to drilling problems (high pressures inducing fractures). This mapping and understanding of reservoir heterogeneity is crucial for reservoir management.

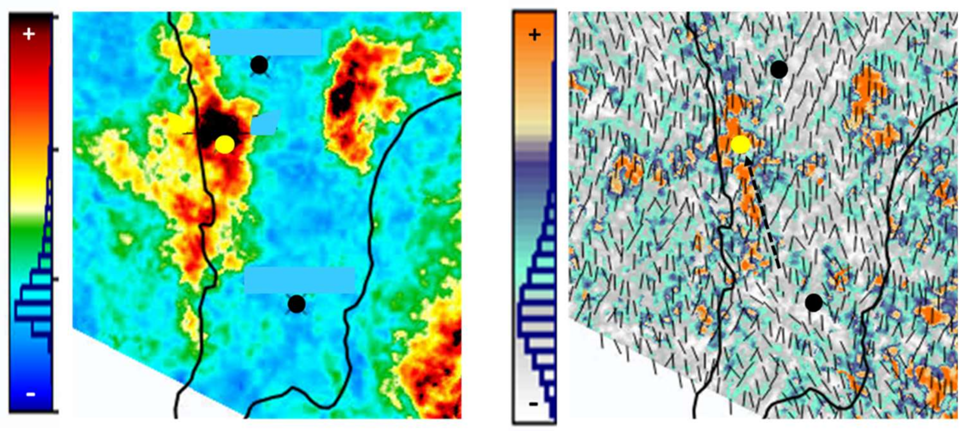

Figure 3: Fracture density (left) and isotropy plane (fracture strike, right) average maps computed in the reservoir interval.

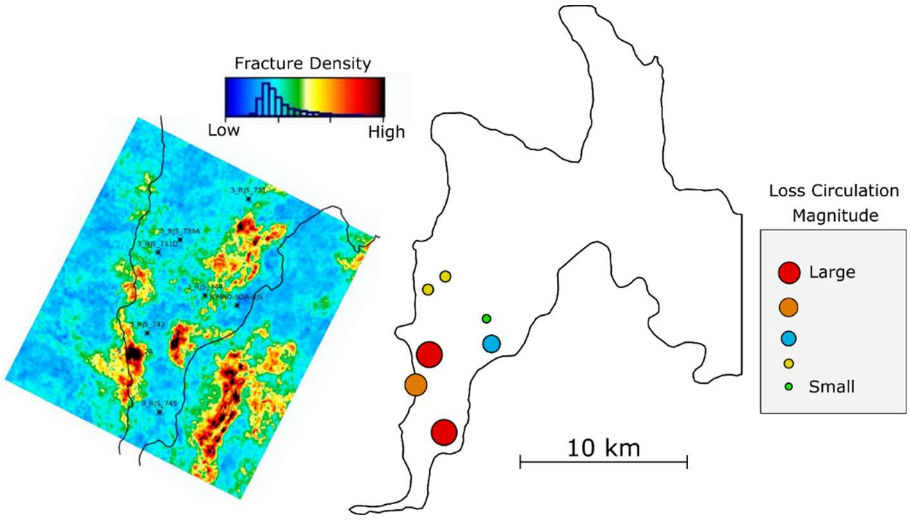

Figure 4: Fluid loss during well drilling and fracture density relation in a certain stratigraphic reservoir level.

Conclusions

Azimuthal inversion has proven to be a key methodology to better characterize possible fractured areas in pre-salt carbonate reservoirs. In the light of new multi-azimuth node acquisitions carried out for the Brazilian pre-salt, this type of study will bring key valuable information for reservoir management. By integrating geology (core and logs) and engineering data, azimuthal inversion was able to help in characterizing the complex pre-salt carbonate fracture system, supporting the flow model update and providing inputs for geomechanical studies.

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