Application of the azimuthal inversion in pre-salt reservoirs for fracture characterization.

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Abstract

The production rates of pre-salt carbonate reservoirs depend on multiple factors, such as the matrix and fracture porosity and permeability. In these dual-porosity dual-permeability reservoirs, the density and geometry of fracture networks play an important role. In this work, we describe a technique of azimuthal elastic inversion using Fourier coefficients, which allows us to improve our knowledge of fractures in these reservoirs. This method is applicable when multi-azimuthal seismic data is available – for example data acquired with ocean bottom nodes. The objective of this work was to characterize the fractures network and improve the knowledge of reservoir production units associated with fractures. The relationships between fracturing and production rates are linked to the in-situ stress field and fracture porosity. We showcase the benefits of the azimuthal Fourier coefficient elastic inversion method on two pre-salt case studies.

Introduction

The pre-salt carbonate reservoirs are very important part of the production portfolio in Brazil. At the same time, these reservoirs represent a significant challenge when it comes to the reservoir model and understanding of its properties and dynamic processes, due to the fracture network. For new well locations and for improving the production of drilled wells, it is paramount to improve the characterization of the fracture network systems and the associated reservoir quality and production (e.g., Tanaka et al., 2022; Aizprua et al., 2019).

Fracture networks and fault zones may act as conduits for fluid flow, thus acting as a major driver for enhancing the porosity and permeability in reservoirs. It is therefore key to understand how these systems work and relate to elastic properties (e.g., Fernández-Ibáñez et al., 2022; Wenneberg et al., 2023).

Recent multi-azimuthal seismic data obtained by nodal acquisition systems contain information about anisotropy. Unlocking this information allows the characterization of the fracture systems. In this work, we present the application of azimuthal elastic inversion as a method to access the anisotropic information contained in amplitude changes associated with azimuth variation.

Method

The azimuthal elastic inversion (Downton and Roure, 2010) is an extension of the isotropic elastic inversion (Coulon et al, 2006).

The technique uses the linear slip deformation theory (Schoenberg, 1980) to estimate fracture properties from azimuthal angle stacks. The result of this method includes isotropic parameters, such as P-velocity, S-Velocity and Density; and anisotropic fracture parameters such as normal and tangential weaknesses and the strike of the fractures. These parameters are layer properties, which makes them easier to interpret than reflectivity or interface attributes, such as the anisotropic gradient (Rüger, 2002). A known limitation of this azimuthal elastic inversion is crosstalk between the isotropic parameters and fracture parameters.

Downton et al. (2010) demonstrated that azimuthal Fourier coefficients can be used to separate the amplitude versus offset (AVO) and amplitude versus azimuth (AVAz) problems, thus reducing the crosstalk between the isotropic and anisotropic parameters. The main idea is that the azimuthal reflectivity can be rearranged as the sum of sine and cosine functions or, in other words, a Fourier series. Equation 1 shows the Fourier series for the linearized P-wave AVAz equation, 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 so higher order terms are ignored.

$$R(\phi,\theta) = u_0(\theta) + v_2(\theta)\sin(2\phi) + u_2(\theta)\cos(2\phi) + v_4(\theta)\sin(4\phi) + u_4(\theta)\cos(4\phi), \quad (1)$$

The term of order 0 is a function of both isotropic parameters and fracture reflectivity. The higher order Fourier coefficients are solely a function of the fracture parameters and the square of the S-wave to P-wave velocity ratio (Vs/Vp) of the unfractured background rock (noted *g*). Theta (θ) corresponds to the angle of incidence and phi (Φ) to the phase of the Fourier coefficients. Given *g*, it is possible to invert these Fourier coefficients to estimate the fracture weakness parameters. The fact that *g* is required still implies that there is a weak coupling between the fracture and background isotropic parameters.

After an optimized AVAz compliant processing workflow, the azimuthal angle stacks are transformed into azimuthal Fourier coefficients, keeping only the 2nd and 4th order terms (Figure 1).

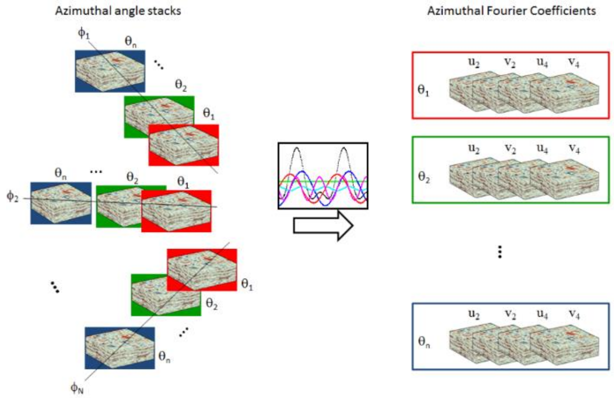

Figure 1. Transformation of the azimuthal angle stacks into azimuthal Fourier coefficients keeping the 2nd and 4th order terms (Roure and Downton, 2012).

Figure 2 illustrates the azimuthal inversion of Fourier coefficients using the 2nd and 4th order azimuthal Fourier coefficients as input data, and an initial model of the isotropic and anisotropic parameters to be perturbated during inversion. The 0-order Fourier coefficient is not included into this scheme in order to separate the isotropic and anisotropic problem. The cost function minimized during inversion consists of three terms. The first term corresponds to the misfit between the real seismic data and the modelled data calculated by the convolution of its reflectivity using 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. Simulated annealing is used for the cost function minimization.

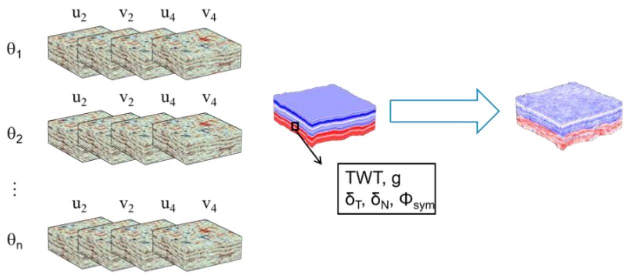

Figure 2. Azimuthal inversion of Fourier coefficients using the 2nd and 4th order azimuthal Fourier coefficients as input data, and the initial model of the isotropic and anisotropic parameters to be perturbed during inversion.

The output of this method includes isotropic parameters such as P-velocity, S-Velocity, Density, and fracture parameters such as normal and tangential weaknesses and the strike of the fractures. The tangential weakness controls the fracture response to shear stress and is directly associated with the crack density. The normal weakness controls the fracture response to normal stress and is associated with the crack density and fluid content (Schoenberg, 1980). The strike of the factures shows the preferential fracture direction. Complementary attributes can be extracted from the inversion results – for example the crack density, that can be derived from a combination of tangential weakness and g.

Application to pre-salt cases

In this work we show the application of the azimuthal Fourier coefficients elastic inversion in two pre-salt fields, denoted as “field M” and “field T. The results are integrated with the available information from reservoir engineering and geology.

The potential of recovering information about anisotropy from the seismic data is directly related to the quality of the data. The uncertainty of the result comes from noise, both isotropic and anisotropic, contained in seismic data and the crosstalk between them. The multi-azimuthal seismic data acquisition, the seismic data processing for the purpose of anisotropy analysis, and the inversion that allows to separate the isotropic and anisotropic effects, all act together as factors to decrease the uncertainty of the results.

Validating the results of fracture estimates is one of the challenges when working with these methodologies (Downton et al., 2011). The dipolar sonic can serve as a reference for evaluating the results by comparing it directly with inversion result, in the same way as is done for isotropic elastic inversion. The challenge comes from the fact that dipolar sonic is usually available in very few wells. Additionally, fracture predicting seismic attributes (e.g., maximum curvature, anisotropic gradient by near offset Rüger equation), engineering data, and prior geological knowledge of the area can be used to validate the azimuthal inversion result. However, fractures and anisotropy are not the only factors impacting these and usually a simple correlation cannot be established.

Before analyzing the results in terms of geological features, we checked the consistency of the results with the Fourier coefficients by evaluating the inversion residuals. This allowed us to verify where it is possible to have more confidence in the estimated properties.

In the field M, the inversion used an initial model of weakness properties created by kriging the well log data – dipolar sonic log was available in 5 wells in the analysis area. 12 azimuthal seismic sectors were available for the inversion. Figure 3 shows maps of the average values of the tangential weakness extracted from one of the stratigraphic units of the reservoir – both from the initial model (A) and the inversion result (B). We can see that the main anomaly’s location is significantly controlled by the initial model, but the shape, size and intensity of all anomalies is controlled by the seismic response. The same observation is valid for the normal weakness (Figure 4).

The crack density was calculated in the reservoir interval from the inversion results. It is shown in Figure 5, overlaid with the strikes of the fractures which are shown as direction planes.

To try to establish a relationship between the amount of fracturing and the field's production, we compared the inversion results with the magnitude of fluid circulation loss during drilling (Figure 6, right). The loss of fluid circulation during well drilling in the western region correlates visually with the high fracturing amount for this area. Furthermore, the westernmost well (orange circle in Figure 6, right) is one of the best producing wells in this area, which may be related to the NW-trending fractures around it. As discussed in Mendes et al. (2022) for another pre-salt case, this study may help further understand the role that fractures or fault structures may have on permeability, which can be directly associated with the well productivity. However, there is no direct correlation between the magnitude of circulation loss and crack density, which probably comes both from noise in the seismic and from the fact that the loss of circulation is not only impacted by fractures.

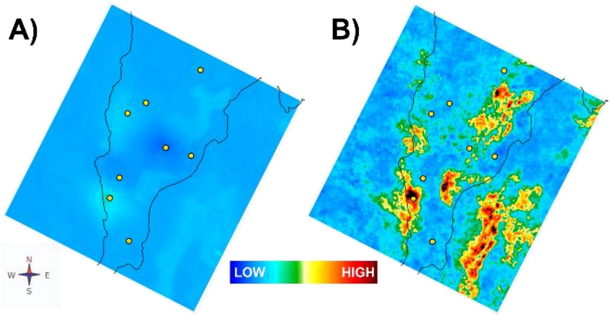

Figure 3. Average tangential weakness in one of the stratigraphic units of field M. Initial model (A) and azimuthal inversion result (B).

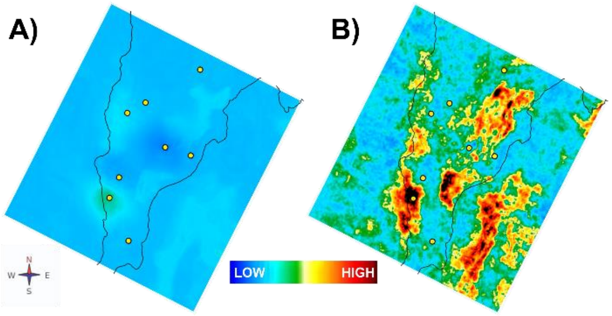

Figure 4. Average normal weakness in one of the stratigraphic units of field M. Initial model (A) and azimuthal inversion result (B).

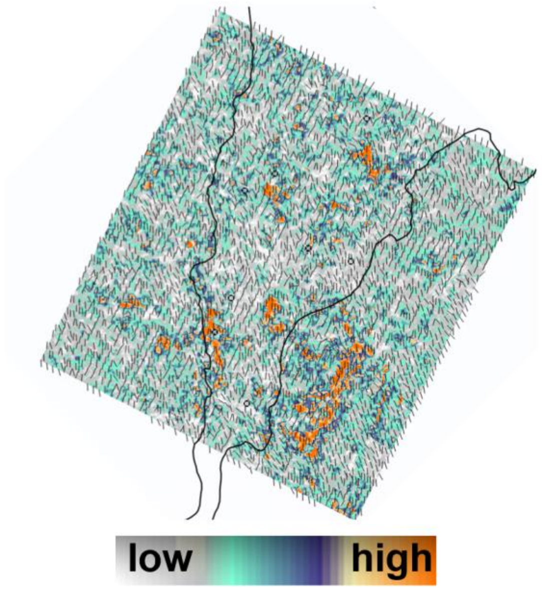

Figure 5. Crack density calculated from inversion results in one of the stratigraphic units of field M overlaid with fracture direction planes.

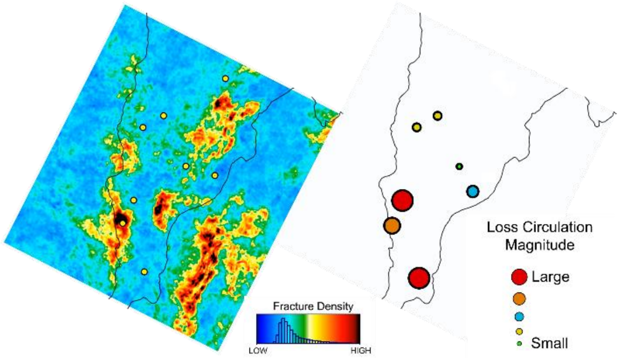

Figure 6. Crack density (left) and fluid loss during well drilling (right) in one of the stratigraphic units of field M.

In the field T we had access to dipolar sonic log in one single well only. This fact limited us in the construction of the initial model of the tangential and normal weaknesses, which did not contain any lateral variation. The anisotropy parameters obtained in the inversion are therefore purely driven by the input seismic data. 18 azimuthal sectors were available for the inversion. The crack density calculated from the inversion result was interpreted with the maximum curvature as an independent attribute.

According to the conceptual model of the area, the intensity of fractures and the thickness of the damage zone is related to the distance to the faults and their displacement. A greater intensity of fractures is observed in the lower portion of the reservoir (Figure 7C) which is associated with a rift phase and greater tectonic activity. This fracturing probably occurred during the formation of the sedimentary basin. Going up in the section, there is progressively less fracturing. The Barra Velha Formation and in particular the BVE100 and BVE200 units which are most productive, are characterized by tectonic quiescence with fault vertical throws lower than for the deeper parts of the section, which is reflected in the lower crack density on the inversion results (Figure 7A and B).

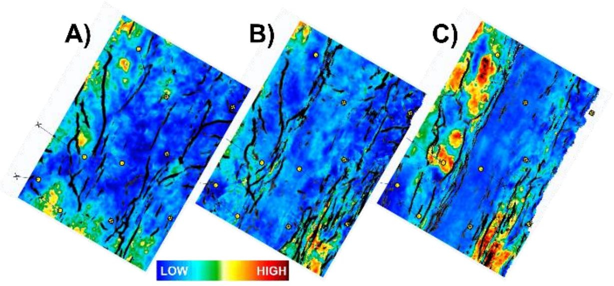

Figure 7. Crack density calculated from inversion results in three stratigraphic units of field T, overlaid with the maximum curvature zones in gray colors. A) BVE100 B) BVE200 and C) lower reservoir zone.

Conclusions

The ability to extract direct information about crack density and fracture direction from multi-azimuthal seismic data can help to better understand the reservoir and to optimize production. The azimuthal Fourier coefficients elastic inversion is a method developed for this objective. It is important to validate inversion results with dipolar sonic logs in wells when available and with other types of complementary reservoir information such as fracture predicting seismic attributes (maximum curvature, anisotropic gradient by near offset Ruger equation), engineering data, and prior geological knowledge of the area. This enhances the understanding of the uncertainty contained in the obtained anisotropic parameters. The method proved to be valuable in the pre-salt reservoirs where fracture network systems have influence on production rates.

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