Multi-azimuth seismic inversion workflow optimization for anisotropy estimation

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Abstract

The quality of seismic images is crucial in the exploration and production stages of a hydrocarbon reservoir. Good seismic quality can lead to the development of reservoir models with a more accurate target description. The ability to perform seismic acquisitions with a good azimuthal coverage can be valuable for anisotropy estimation leading to better fracture and overall system characterization.

This study proposes to improve a deterministic model-based seismic inversion workflow building upon multi-azimuth seismic data workflow already existent. A new wavelet use is proposed, using a single wavelet for all azimuthal sectors instead of different wavelets per sector. This modification seeks to reduce the artificial anisotropy induced by the minimal differences between wavelets of different amplitudes, leading to a more accurate result. The study also deals with the optimization of the multi-azimuth seismic inversion parameters, promoting the characterization and quantification of the anisotropy present in the dataset.

This thesis is centered around two types of deterministic inversions (sequential and joint), specific to azimuthal data, and how they can be used in anisotropy quantification. Several optimizations are performed to the parameters used by the sequential and joint inversions so that both can produce similar results which are needed for the anisotropy analysis. The anisotropic analysis is the key element of the thesis, the objective of using multi-azimuth seismic data is to detect anisotropic anomalies and characterize them. The thesis will develop the workflow for multi-azimuth seismic data inversion and will interpret the data regarding the origin of the existing anisotropy.

Keywords: Seismic inversion, azimuthal inversion, seismic anisotropy

1. Introduction

The Oil and Gas industry has a footprint present in every corner of the world. Its role in the energy market, economy, politics, development is undisputedly high. Like any industry, is subject to new challenges, and so, factors like efficiency, cost optimization and environment have been increasingly important to drive the industry further [1],[2] .

In a competitive world, the search for the best results is essential to secure business opportunities. Decisions need to be accurate, and so needs to be the knowledge behind it. The oil and gas upstream stages based on seismic amplitude analysis are fundamental in the decision making. Knowledge provided by seismic inversion is fundamental in the exploration and production of hydrocarbons, through it is possible to create models of the subsurface of the earth and identify geological formations prone to hydrocarbon accumulation. Naturally, significant developments are being made in the way that seismic data is applied in the industry, especially in the use of 3D seismic to identify geological structures and to predict reservoir properties accurately to avoid missing exploration opportunities [3].

Conventional 3D seismic surveys use a single line of orientation, this is, narrow-azimuth (NAZ), which results in illuminating only one shooting direction. However, for complex geological areas something more is necessary. When coherent noise is too complicated to be interpreted and the reservoir illumination is irregular or discontinuous, different approaches are necessary to answer these problems and ensure that the best possible decision is made to avoid expensive failures. These difficulties drove the development of more complete survey strategies to achieve better reservoir identification such as multi-azimuth (MAZ), wide-azimuth (WAZ) and rich-azimuth (RAZ) surveys which started to be widely used on more challenging areas [4].

Acquiring seismic data using MAZ surveys and performing deterministic model-based inversions can be a useful tool to identify seismic anisotropy and better characterize fracture parameters with origin in azimuthal P-wave data that otherwise would be left unnoticed. If the results are satisfactory, a more accurate analysis of the system is possible, thus, maximizing the confidence in the created model of the subsurface.

This thesis results in the work performed during an internship at Beicip-Franlab, an international oil and gas consulting and software provider. The work explores the MAZ seismic inversion module of InterWell®, the seismic inversion and characterization software for reservoir and exploration geophysicists developed by Beicip-Franlab.

2. Literature

This section provides the relevant theoretical background necessary in the elaboration of the thesis.

2.1 Seismic inversion

Geophysical methods study the propagation of physical fields inside the earth, measuring its response to determine and describe complex geological structures. The earth´s measured feedback which describe the physical system is determined by the rock properties. This knowledge allows geophysicists to make predictions and create subsurface models. To build these subsurface geological models different approaches can be used. The laws of physics provide the means to compute measurements given a model, this is called *forward problem*. It is also possible to use the results of some measurements to predict the values of the parameters that characterize the system, explaining the observed data while taking uncertainty into consideration, this is called the *inverse problem* [5].

While forward problems allow, considering an earth model, to predict the values of seismic signals, for other geophysical applications, such as seismic inversion, the opposite is needed, this is, to create a model of the earth given measured signals at a specific location [6]. Seismic inversion can be briefly defined as a technique for creating a model of the earth from observed data. As the name hints, seismic inversion, being an inverse problem, directly opposes the forward approach [7]. The main goal when using seismic inversion methods is to predict reservoir properties and characterize rock properties such as lithology, porosity, fluid content as well as the conditions to which they are subjected, like pressure and temperature [8]. The seismic data inversion presents practical challenges, for instance, noise being always present in the data, forward modeling simplifications need to acquire solutions in reasonable time, uncertainties when estimation a wavelet and difficulties when associating reservoir and elastic properties [8].

2.2 Deterministic seismic inversion

In general there are two main groups for seismic inversion methods, the deterministic and the stochastic [8], [3]. Deterministic inversions consist in the minimization of the difference between a modeled seismic trace and the actual trace, and are therefore based on optimization algorithms that aim for a single best fit solution [9], [3], [8]. Additional terms are usually included in the objective function to condition the solution into fitting a specific criteria [8]. Within stochastic inversions geostatistical inversions are based on geostatistical simulations to generate diverse realizations at reservoir model scale. Each realization can be matched to the seismic trace, honoring the statistics of property variation between points and teeing the wells precisely. These realizations can be turned into reservoir properties and analyzed in terms of uncertainty as well as connectivity [3].

There are several deterministic methods, being the most commonly used the sparse-spike techniques and model-based inversions [8]. Sparse-Spike Inversion (SSI) consists in a group of techniques where the seismic trace can be modeled with reduced, but large, reflection coefficients (spikes). Model-based inversions are a popular inversion technique for commercial software [3]. In this type of inversions there is an initial impedance model that provides the low frequency component not present in the seismic bandwidth. The model is convolved with the wavelet to obtain a response which is compared with the seismic and constantly updated until the seismic response fits the seismic data upon some determined criteria where the errors are minimized [3], [7], [10]. The starting model can be an interpolation of well data or a trend model based on geological knowledge [3]. This is an appealing method since it avoids the direct inversion of the seismic data itself, however, at the same time is possible to obtain a model that matches the seismic data perfectly but is incorrect [7].

2.3 Azimuthal seismic acquisition

Achieve acceptable mapping of the subsurface properties is a challenging process, therefore, alternative acquisition methods dedicated to successfully illuminate and create 3D models of the most complex geological structures are needed. For this purpose, seismic acquisition techniques have been developed, using not only gathers by offset, but also by azimuth.

There are several methodologies for azimuthal acquisition, such as NAZ, MAZ and WAZ [4], [11], [12]. Conventional 3D marine surveys are acquired using a long and narrow spread of streamers that are towed by one ship (in marine acquisition) resulting to sources and receivers having a relatively common azimuth causing the subsurface to be mapped in that shooting direction. This is the case for the NAZ survey. This type of acquisition assumes that the target to map is fairly uniform which allows to create clean seismic images capable of accomplishing the proposed exploration and appraisal objectives. However, when the target is too complex, and the coherent noise is too complicated thus preventing the interpretation of the subsurface, other techniques could be used [4]. This is the case for MAZ and WAZ. MAZ methodology is the combination of several NAZ surveys on the same target but from different shooting directions providing a better-quality target illumination [4], [12]. WAZ surveys are similar to NAZ with the difference of offering a much wider azimuthal angle. This is achieved by using a higher aspect ratio (i.e. crossline dimension of the patch divided by the inline dimension) of the recording patch. Aspect ratios until 0.5 are considered NAZ, while greater than 0.5 are considered WAZ [11]. In a marine acquisition the WAZ survey is performed usually by adding one or more source vessels [12]. Narrow, multi and wide azimuthal acquisitions represent just some of the possible methods for azimuthal survey, for instance, combining MAZ and WAZ techniques result in another called RAZ [4].

2.4 Seismic anisotropy

Anisotropy is defined as the *"variation of a physical property depending on the direction in which it is measured"* [13]. Seismic anisotropy can therefore be defined as a *"directional variation of a material's response to the passage of seismic (elastic) waves"* [14]. The role of anisotropy has rapidly increase in the past two decades and is important in geophysics due to its inevitable impact on seismic data [14].

The most common anisotropy model is transverse isotropy (TI). In materials following this anisotropic model there is only one rotational symmetry axis, and so, in directions perpendicular to that same axis, the material properties appear to be directionally invariant. When the symmetry axis is vertical it is called vertical transverse isotropy (VTI), when it is horizontal is called horizontal transverse isotropy (HTI) [14], [15]. Anisotropy is interesting to consider mainly for two purposes, firstly to improve seismic images by considering VTI as anisotropy during the processing of the seismic data, attribute analysis and interpretation and secondly to extract fracture information from seismic data [14].

3. Methodology

This section addresses the methodology applied in this thesis. To achieve the proposed objectives, its necessary go through InterWell® (Beicip-Franlab) key steps, such as the seismic alignment (residual normal moveout correction), wavelet extraction and *a priori* model before the inversion. However, the focus is in the inversion process and consequent results. The azimuthal inversion module of the software was designed to take advantage of the MAZ seismic acquisition to highlight possible impedance anomalies that otherwise would be very hard to detect.

3.1 Wavelet extraction

The extraction and optimization of the wavelet is an essential process in any seismic inversion work.

The normal methodology for the wavelet extraction implies the use of different wavelets, unique for each azimuthal stack. However, using different wavelets in theory should induce unwanted artificial anisotropy during the inversion process. To test this hypothesis, four wavelet scenarios are proposed and explored. The first is to use the original workflow as a comparison basis, this is, using a different wavelet per stack as originally designed. The second scenario is to choose one of the wavelets extracted and use it for all stacks. All the wavelets should be very similar since they represent the same events, so an arbitrary choice should not make any difference. The third scenario is to perform an average of all the wavelets and use it for all stacks. Finally, the fourth and last scenario is to compute an average of the azimuthal seismic stacks, thus creating a fullstack, and extract a single wavelet from it. This wavelet will then be used for all stacks during the inversion. The purpose of three different scenarios using the same methodology (single wavelet for all azimuthal stacks) is merely to find if some is more adequate than the others.

3.2 MAZ seismic inversion

Two inversion sub-types are available in this module, one that performs the inversion on each stack individually, resulting in different outputs per stack (i.e. sequential inversion), and another that combines all stacks delivering only one output for the entire inversion (i.e. joint inversion).

Sequential inversions are multi-channel model-based inversions that optimize the impedance distribution of each stack individually, resulting in different impedance volumes (equal to the number of stacks) that posteriorly to the inversion can be analyzed regarding the intensity and orientation of the anisotropy through ellipse fitting because each stack remains unique and so anisotropically different from the others. This way, sequential inversions are considered to retain not only the isotropic contribution but also the anisotropic contribution as each output corresponds to a unique stack. Joint inversions are also multi-channel model-based inversions but combine all azimuthal stacks in the inversion, and so, the single output only retain the isotropic contribution of the available seismic volumes, the similar part of all stacks. For this reason, the output of the joint inversion is considered to reflect only the isotropic contribution of the azimuthal seismic data. By subtracting the sequential and joint inversions results a residual impedance value which corresponds to the anisotropic contribution of each stack.

One challenge, however, is the choice of parameters to use when performing the sequential and joint inversions. The parameters are the impedance standard deviation (ISD) and the seismic noise/signal ratio. Both regulate the weight of seismic and the *a priori* model to be used during the inversion.

Because the inversions (sequential and joint) are different and done separately the parameters used in one might not serve to the other. This occurs because the sequential inversion processes one stack at a time while the joint inversion processes them all together. It is therefore needed to find a link between them that provides good compatibility since both outputs are combined afterwards to make anisotropy related estimations. The parameter optimization will be one of the most important and challenging tasks to complete in the entire workflow.

3.3 Parameter optimization

To use the sequential and joint inversions the output must be similar. To search for a relationship between the parameters of both inversions a study on how to link them was developed.

The methodology used to link both inversions was simply to keep the Seismic noise/signal value to default and experiment with ISD to find which set of values are needed. Because both parameters represent the seismic/model balance, working them simultaneously would be much harder and for that reason one is kept fix in the default value while the other is being experimented. The starting point was to use the same set of parameters on both inversions and then progressively increase one or the other until the difference between the impedance on both inversions is minimum. Another important parameter to keep track is the cost function, this indicates the convergence of the inversion by pointing the percentage of seismic and therefore model that was used. Ideally, the cost function should be very similar in both inversions.

4. Application and results

In this section the results of the parameter optimization will be evaluated and used in the anisotropic analysis.

4.1 Data description

The used dataset originates from Kuwait and has inlines ranging from 27799 to 29499 and xlines ranging from 103699 to 105199. The time interval is from 1000ms to 3000ms and the sample rate is 4ms. The survey also has available twenty wells used for the wavelet estimation and *a priori* model.

4.2 Wavelet application

Different approaches regarding the way the wavelet is applied for azimuthal inversion in InterWell® (Beicip-Franlab) were explored. Three scenarios were proposed where a single wavelet was considered for all azimuthal stacks instead of different wavelets per stack, to minimize any artificial anisotropy. However, the main objective was to evaluate the single versus multiple wavelet scenario, and not the differences between the new scenarios themselves.

Further testing demonstrated that between all the single wavelet scenarios the differences were minimal, and so, the option used to carry on the inversion was the second scenario where a wavelet from one of the azimuthal stacks was used for all the others as well. The second scenario was chosen not only to reduce any artificial anisotropy but also because was the easiest to implement in the single wavelet scenario.

4.3 Parameter optimization

Several attempts were made to find a set of parameters that produce equal results on both inversions (sequential and joint). The standard value for the ISD is 800 and a range of values between 400 and 1600 were tested, with either the parameter equal in both inversions, higher value in sequential inversion or higher value for the joint inversion.

After experimenting with the different possibilities of combining the parameters the best results are achieved when the sequential inversion ISD parameter is twice the joint inversion ISD parameter. With similar parameters or with the joint inversion ISD parameter higher than the sequential inversion ISD parameter the discrepancy in cost function and impedance values is high. In Figure 1 is an example of ISD parameters equal in both inversions and in Figure 2 is an example of the sequential inversion ISD parameter being the double of the joint inversion ISD parameter which demonstrates lower residual impedance values.

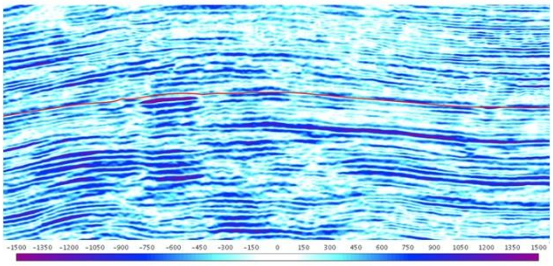

Figure 1 - 1st parametrization residual xline cross-section of the target area (1800ms - 2800ms), performed by subtracting the results of one inversion from the other (sequential - joint).

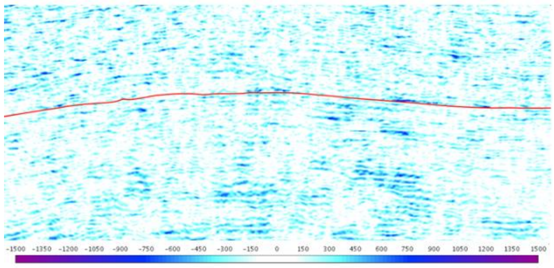

Figure 2 - 9th parametrization residual xline cross-section of the target area (1800ms - 2800ms), performed by subtracting the results of one inversion from the other (sequential - joint).

4.4 Anisotropy quantification

There are two workflows available in InterWell® (Beicip-Franlab) software. The first one, is focused on the residual impedance values while the second provides several tools to quantify the anisotropy itself. Now, using all the resources provided from both workflows and combining them with all information available, is possible to conceive a hypothesis regarding what is in the origin of certain anisotropic anomalous areas.

The hypothesis presented was that the source of the anisotropy could primarily come from either the lithology or a smaller system of fractures. The impedance maps from Figures 3, 4, 5 and 6 indicate three areas (A, B and C) where the lithology transits between lower impedance carbonates and higher impedance anhydrates. These three areas change considerably in each sector and correspond to high anisotropic values (Figure 7) and so, part of the anisotropy could come from the transition between lithologies. Also from Figures 3, 4, 5 and 6 areas D and E appear to be stable in terms of impedance, however, in Figure 7 correspond to a high anisotropy ratio. This excludes the lithology as the anisotropic source for these areas and by looking into the residual impedance (sequential inversion - joint inversion) in Figures 8 and 9 is visible that both areas are better detected in a specific sector and less in the other. This indicates a possibility of having fractures invisible to a shooting direction and visible to other, and therefore, the source of the anisotropy in these areas is assumed to be a small fracture system. In area F there is a high cluster of anisotropy (Figure 7) with considerable variations in impedance (Figures 3, 4, 5 and 6) and also in residual impedance between sectors (Figures 8 and 9) which indicate that both the lithology and fractures could explain the high anisotropic values.

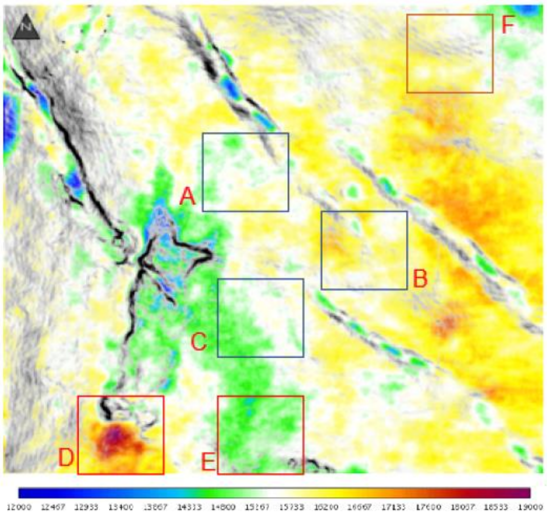

Figure 3 - Map of the area of interest, provided by the sequential inversion, which delineates the acoustic impedance of the first sector. There are represented six subareas of interest are marked with the letters A, B, C, D, E, F.

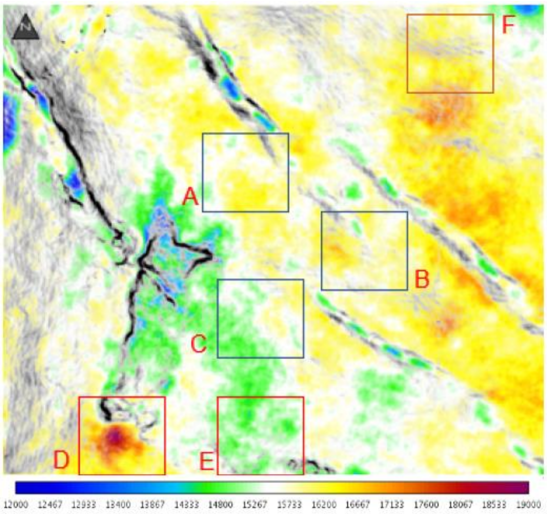

Figure 4 - Map of the area of interest, provided by the sequential inversion, which delineates the acoustic impedance of the second sector. There are represented six subareas of interest are marked with the letters A, B, C, D, E, F.

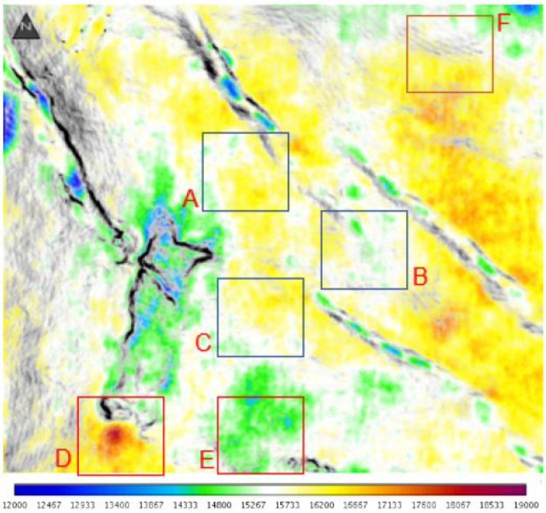

Figure 5 - Map of the area of interest, provided by the sequential inversion, which delineates the acoustic impedance of the third sector. There are represented six subareas of interest are marked with the letters A, B, C, D, E, F.

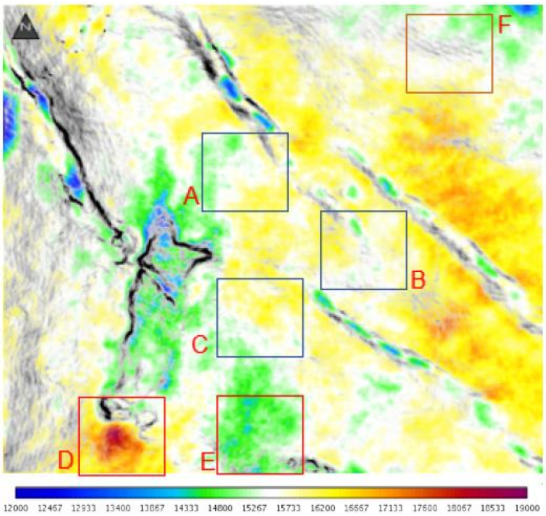

Figure 6 - Map of the area of interest, provided by the sequential inversion, which delineates the acoustic impedance of the fourth sector. There are represented six subareas of interest are marked with the letters A, B, C, D, E, F.

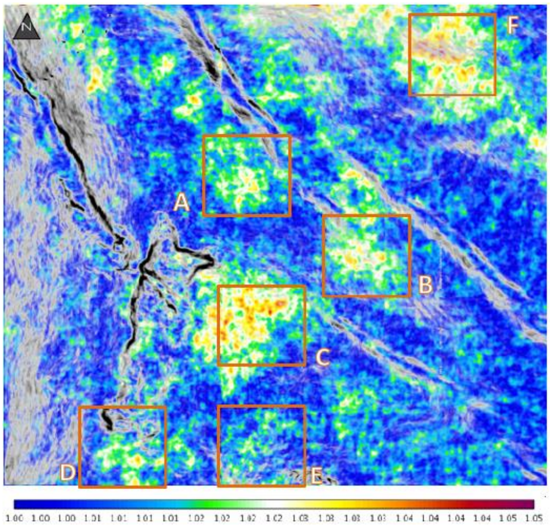

Figure 7 - Map of the area of interest which delineates the anisotropy ratio on top of the fracture system. Additionally, six subareas of interest are marked with the letters A, B, C, D, E, F.

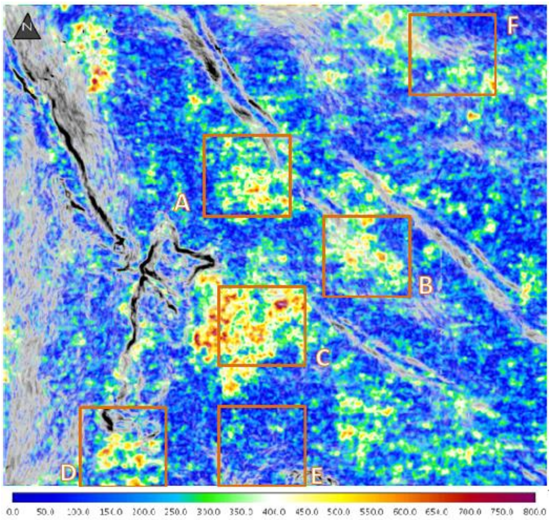

Figure 8 - Map of interest which delineates the residual impedance values (sequential inversion - joint inversion) from the first sector. Additionally, six subareas of interest are marked with the letters A, B, C, D, E, F.

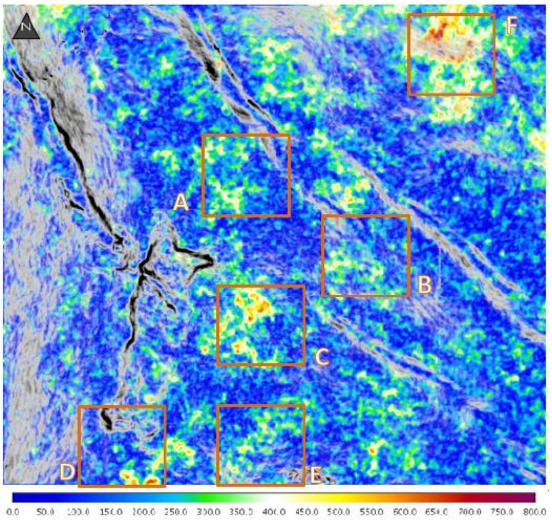

Figure 9 - Map of interest which delineates the residual impedance values (sequential inversion - joint inversion) from the second sector. Additionally, six subareas of interest are marked with the letters A, B, C, D, E, F.

4.5 Secondary results

This section is dedicated to present results that are not the main focus of the thesis. Here an alternative to the joint inversion will be proposed and the impact that using one wavelet has, or not, when comparing to the standard multi wavelet scenario will be evaluated.

4.5.1 Using the fullstack as an alternative for the joint inversion

An alternative to the joint inversion was idealized to simplify parameters and to be computationally less demanding. The idea is to create a fullstack with all seismic sectors and run a standard deterministic inversion instead of the joint inversion where all sectors are combined in the inversion process. Using this method, the inversion obtained is very similar to the joint inversion, uses the same parameters as the sequential inversion and takes, in this case, a quarter of memory in the inversion process.

4.5.2 Wavelet influence

The wavelet approach was different from what is by default used in MAZ inversion module of InterWell® (Beicip-Franlab). The intention was to reduce artificial anisotropy caused by using different wavelets to represent the same seismic event. In this dataset there are minor changes when using four different wavelets but overall, the results are consistent no matter the used wavelet methodology.

5. Conclusions

This thesis addresses the topic of seismic anisotropy and how azimuthal seismic data can be processed to support a better interpretation of the subsurface. By using multi-azimuthal seismic data is possible to map in detail complex geological structures and to determine the source of the detected anisotropy.

In this work the objective of improving the methodology for the multi-azimuth seismic inversion was achieved, even though the wavelet methodology did not had the a significant impact the parameter optimization provided solid information on how to proceed with the sequential and joint inversions. Additionally, an alternative for the joint inversion was formulated to simplify the choice of parameters and to reduce the necessary computer memory for the inversion. Finally, hypothesis were proposed as the origin of the anisotropy in the target area possible only by using multi-azimuth seismic.

5.1 Future work

The theme exposed in this thesis is still very superficial with a large room for improvement. The wavelet methodology should be experimented with different datasets to conduct a more rigorous analysis if the impact in the results is significant or not. Also, a more in-depth study of the well data should be done to have a better understanding of the lithology to validate if indeed is a cause for anisotropy. Finally, the complete detailed interpretation and characterization of the fracture system should be the final objective and is still not accomplished.

6. References

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