Impact of wavelet extraction in the seismic reservoir characterization: Real case study.

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Abstract: This thesis shows a real case application where different wavelet scenarios, extracted under different parameterization assumptions, were considered in stochastic acoustic inversion. The inverted acoustic impedance models, retrieved from these different wavelet scenarios, were compared in order to assess the impact of wavelet extraction method and parameterization in the exploration of the uncertainty space globally and locally around the well locations by computing statistical measurements. Additionally, multidimensional scaling (MDS) was used as a statistical tool to quantify the differences from the resulting acoustic impedance models, reproduced under the different wavelet scenarios. Stochastic inversion methodology together with MDS prove to be a powerful tool to assess and quantify the uncertainties associated to generated models, under different wavelet scenarios with different uncertainties associated, helping understand how the real parameters space are being explored. When used unreliable wavelets, in particular for the extracted using the Constant Phase method, the generated synthetic data struggled to reproduce the recorded seismic data, resulting in high uncertain models, impairing the ability to explore the real model parameter space. In the MDS plot, best-fit acoustic impedance models that result from wavelets extracted using Roy White method are more similar and with lower uncertainties even if considered an unreliable wavelet scenario. The previous methods of extraction use well logs in addition to seismic data. Statistical wavelets, estimated base on seismic data, generate best-fit models that are reflecting a mean behavior of real parameter’s characteristics.

Keywords: Stochastic seismic inversion, geostatistical seismic inversion, uncertainty assessment, quantify uncertainties, wavelet extraction.

1. Introduction

The traditional use of seismic data in exploration and development is at first stage for structural mapping, aiming the identification and evaluation of traps that could contain hydrocarbons and the expected volumes. Seismic data can be used, in a more advanced stage to infer reservoir rock properties, converting the interface seismic data into stratigraphic data by using different seismic inversion methodologies, which can then be directly compared with the drilling and logging data. Both well and geophysical data used as inputs to solve any inversion process, have their own uncertainties associated to error
measurements, processing and interpretation. In addition, the process used to infer the rock properties, the inversion process, incur to uncertainties because their intrinsic characteristics such as non-linearity, ill-conditioned with non-unique solutions (Tarantola, 2005 and Bosch et al., 2010). By making use of rock-physics models, that relate the elastic properties to reservoir properties such as pore volume, fluid type, and reservoir connectivity, with direct impact in the economics of hydrocarbon reservoirs, can be estimated and lateral reservoir variation can be analyzed (Bosch et al., 2010). With stochastic seismic inversion, it is possible not only to characterize the elastic behavior inside a certain area, but also to assess the uncertainties of the estimated rock properties (Dubrul, 2003 and Bosch et al., 2010), helping in the decision-making during the exploration and production phases essential for reducing development and drilling risks with negative economic implications. Being the seismic wavelet the link between seismic data and rock properties of the subsurface (White, 1996) it is extremely important to estimate and properly characterize the wavelet for a particular seismic dataset and to derive reliable inversions products. Wavelets can be estimated deterministically, statistically by using only seismic data and using well data in addition to seismic (Russel, 1999). Parameters as wavelet length (L) and seismic time window (T), must be carefully selected so the resulting wavelets are statistically representative and reliable according to main target and inversion purpose (White, 1996; Russel, 1999 & 2017 and Simm & Bacon, 2014).

The objective of this work is first to compare and evaluate different wavelet extraction methodologies with different parametrization. Then, analyze the impact of using different wavelets scenarios with different ranges of uncertainties associated, in geostatistical seismic inversion with a global approach - GSI. Finally, in order to compare and identify the main differences that may occur in the resulting acoustic impedance models, as a result of the wavelet extraction procedure, and to understand how the wavelets uncertainties affect the exploration of the model parameter space, it was used the concept of distance by applying a statistical tool called multidimensional scale (MDS).

Seismic inversion

Seismic inversion is a technique for creating models that characterize the subsurface based on the recorded seismic data. It can be considered as the opposite of the forward modelling (Russell, 1988) which involves creating a synthetic seismic data based on a model of the Earth (using a sonic log as a one-dimensional model). For both procedures, the use of wavelets is necessary. The most basic and commonly used one-dimensional model for the seismic trace is referred to as the convolutional model, which states that the seismic trace, is the convolution of the Earth’s reflectivity with a seismic source function, the wavelet, with the addition of a noise component. A simpler assumption is to consider the noise component to be zero, and in this case, the seismic trace is simply the convolution of a seismic wavelet with the Earth’s reflectivity.

The inversion of seismic data for elastic properties can be posed as a deterministic or as a stochastic problem (Francis, 2005; Bosch et al., 2010 and Simm & Bacon, 2014). Deterministic methods are based on error minimization between the forward convolution of the reflectivity from an estimated impedance profile and the seismic amplitudes at each trace location. They provide a single local smooth estimate of the subsurface elastic properties, with inaccurate assessment of
uncertainty, moreover tend to exaggerate reservoir connectivity and underestimate reservoir volumes leading to biased estimates. Whereas, the stochastic inversion methods provide multiple solutions, all conditioned to the seismic and well data, allowing better estimates of volumes and connectivity along with an appropriate and crucially important uncertainty assessment (Francis, 2005 and Bosch et al., 2010). Whether deterministic or stochastic, seismic-inversion workflows require forward seismic modelling and most common approach has been based on the convolutional model (Bosch et al., 2010). Two different stochastic approaches can be used to solve the seismic inversion problems (Bosch et al., 2010 and Azevedo & Soares, 2017). The linearized Bayesian inversion, based on a particular solution of the inverse problem under the Bayesian framework and assuming the parameters and observations to be multi-Gaussian distributed as well as the data error, and the iterative geostatistical seismic inversion method that approaches the seismic inversion as an optimization problem in an iterative and convergent process.

In 2007, Soares et al. proposed an iterative geostatistical seismic inversion methodology based on a direct sequential simulation (Soares, 2001) and co-simulation. This methodology uses a global approach during the stochastic sequential simulation stage and for its implementation, it is not necessary to transform any of the used variable, additionally areas of low signal-to-noise ratio remain poorly matched throughout this inversion procedure, classified as uncertain. By using this methodology, it is possible to reproduce the main spatial continuity patterns of elastic and acoustic properties, and petrophysical properties models and assess the uncertainty attached to those models (Soares et al., 2007 and Azevedo & Soares, 2017). This approach can be used to estimate acoustic impedance models, by using global geostatistical acoustic inversion methodology – GSI (Soares et al., 2007) and to more complex inversion process as the inversion of elastic properties - GEI (Nunes et al., 2012), geostatistical seismic AVA inversion (Azevedo et al., in 2013) and geostatistical seismic AVA inversion to Facies (Azevedo & Soares, 2017).

Wavelet extraction

The link between seismic data and rock properties of the subsurface are seismic wavelets (White, 1996). The accuracy and reliability of its estimation is going to affect directly on the quality of the resulting inversion models and will vary depending on the data and what the inversion result will be used for (accuracy to generate absolute impedance should be lower than 10°). When extracting wavelets, two parameters need to be properly defined, the wavelet length (L) and seismic segment or seismic window (T). In order to match measures, such as the cross correlation, to be statistically meaningful, L and T need to satisfy the following relations (White, 1996 and Simm & Bacon, 2014): spectral smoothing factor (bT) needs to be higher than 6, where b is the analysis bandwidth; while b/B should be between 0.25 and 0.50, where B is the statistical bandwidth estimated from the data.

Wavelet extraction methods (Russell, 1999) can be statistical where is determined the wavelet using only seismic data, this procedure tend to struggle while determining the phase spectrum reliably so this need to be supplied in advance; moreover, using well log data. When well data is considered, it is possible to determine both the full amplitude and phase spectrum of the wavelet, using the full wavelet method, or to use the log only to determine a constant phase of the wavelets
in combination with the statistical procedure (hybrid approach) by using constant phase method (Russell, 1999). Additionally, the Roy White method can be used to estimate the wavelet by correlating the well log and seismic data (White, 1996; White & Hu, 1998 and White & Simm, 2003) and at the same time diagnostic parameters are obtained allowing to evaluate the reliability of it. The increasing application of 3D seismic for reservoir characterization and management has emphasized the importance of seismic-to-well ties and consequently their accuracy. According to White (1996) well-tie accuracy report, it is essential when trying to quantify uncertainty in seismic lithological interpretation.

2. Methodology

To achieve the objectives proposed under the scope of this thesis, it was applied the global geostatistical acoustic inversion - GSI (Soares et al., 2007) with purpose of generating high resolution acoustic impedance (Ip) models under different wavelet scenarios and assess uncertainties. By analyzing the achieved local and global correlation in addition to variance of Ip models in last iteration, it is assessed the uncertainties from the generated Ip models. Additionally, multidimensional scaling (MDS) was applied as a complimentary statistical tool to assess and quantify the uncertainties related to inverted models under the different wavelet scenarios, estimated under different methods and parametrization, helping to understand the impact of the wavelets in the exploration of true model's parameter space.

Global geostatistical acoustic inversion (GSI)

This stochastic inversion methodology follows the steps described next (Soares et al., 2007 and Azevedo & Soares, 2017). First, it is used direct sequential simulation to simulate a set of N acoustic impedance (Ip) models, for the entire seismic grid, conditioned to the available Ip well-log data and assuming a spatial continuity pattern. After, it is generated of a set of N synthetic seismic volumes by first computing the corresponding normal incidence reflection coefficients (RC) and then convolving these RC with an estimated wavelet representative of the used seismic dataset. Then, it is compared each seismic trace (at the same location and considering different layers) between the recorded seismic and the previous generated synthetic seismic. From this comparison, the synthetic Ip traces with the highest correlation coefficient are stored in an auxiliary volume along with the value of the local correlation coefficients and used as a secondary variable in the next iteration. A new set of N Ip models is built using direct sequential co-simulation conditioned to the available Ip from well-log data, and using the best Ip volumes as secondary variables and local correlation to condition the joint simulation. Finally, the iterative procedure continues until the global correlation between recorded and inverted seismic reflection data reach a certain criteria value. Global correlation value tends to stabilize and converge to a certain value as it is increased the number of iterations and simulations.

Quantify uncertainties in reservoir properties estimation

The uncertainty characterized by a set of Earth models can be represented using the concept of distance, allowing the uncertainty to be analyzed very rapidly (Caers, 2011). Multidimensional scaling (MDS) is a statistical tool for uncertainty assessment in stochastic frameworks that converts a dissimilarity matrix into points, which can then be plotted in a Cartesian space, the MDS space (Cox et al., 2001; Borg & Groenen, 2005).
and Caers, 2011). Initially the dissimilarity matrix is converted into a new matrix by a scalar product and decomposed by eigenvector, where only the first principal components, or eigenvectors, are recollected (Caers, 2011). The application of both GSI and MDS was already performed (Azevedo et al. 2014 and Azevedo & Soares 2017) to evaluate the convergence of the inverse methodology and the impedance model variability among each iteration of the inversion process. MDS prove to be a valuable statistical tool for uncertainty assessment, helping to evaluate how well the retrieved inverse models converge toward the reality and explore the parameter model space.

3. Data set

The area of study is situated close to the coast of the Caspian Sea, Western Kazakhstan and structurally it is located in the western portion of the South Mangyshlak basin. The reservoir interval is characterized seismically by homogeneous, continuous and parallel reflections with low-to-medium amplitude. It has an average thickness ranging from 25 to 30 meters of highly heterogeneous sandstone layers of good reservoir quality, generally very fine grained low acoustic impedance values. For the available 3D Full stack seismic volume, it was initially defined a rectangular pilot area of about 87km$^2$ (13km x 6.7km), that include the five available wells, here referred as wells A-01, A-02, A-03, A-04 and A-05. A grid was defined with 269(i) x 517(j) x100(layers) cells. Besides, Vp and density logs, a time-depth table resulting from a previous seismic-to-well tie were also available for all wells. Well log data was upscaled into the inversion grid and vertical variogram model, based on well data, and horizontal variogram models, based on seismic data, were obtained in order to characterize spatial continuity of the acoustic impedance. All previous tasks were performed using Petrel® (Schlumberger) software. Using Geoview® (CGG) software, several wavelets were estimated, using both seismic and wells data considering different methods, well sets and parametrization. The methods used to extract representative wavelets were the statistical (STAT), constant phase (CP) and Roy White (RW). Nineteen wavelets were selected and for six of them (related to RW ones) it was available the respective phase error (Figure 1). GSI was run nineteen times were only the wavelet was changed, while all other inputs were kept constant. It was defined for each wavelet scenario a total of six iteration with 32 simulations each. After, the resulting Ip models were plot in MDS space to assess and quantify uncertainties and understand how the model parameter space was explored by analysing the model’s similarities. An additional GSI inversion was performed, using a twentieth wavelet scenario estimated by using the CP method (T of 500ms and L of 260ms using considering all wells), with the objective of assessing properly the impact of using longer wavelets extracted by different method in GSI products.

4. Results and discussion

Global geostatistical acoustic inversion

The global correlation coefficient between real and synthetic seismic volumes is close for almost all the tested wavelets, but in general models generated by using RW wavelets reached higher values when compared to the other methods (Figure 2). In addition, it is observed that as the number of iterations increase (starting from the second iteration) the difference between the resulting global correlation related to RW wavelets tend to decrease while for CP scenarios the difference tend to increase.
When used a statistical wavelet estimated in a seismic window $T$ of 500ms, best global correlation is achieved when compared to statistical wavelets estimated in much larger and smaller windows (2500ms and 100ms with same wavelet length $L$ of 100ms). It was also observed that statistical wavelets obtained with smaller seismic window result in global correlation values higher than when considering the largest seismic window. For the methods that use beside seismic, well data, under same $T$, $L$ and used wells, RW method provided wavelets that generated models that reach higher global performances than CP method resulting models. For same $T$ of 500ms and using all available wells, it was observed that when varying $L$ (60, 100 and 260ms, resulting in a phase error increase) RW wavelets generate similar global correlation values. Main differences occur at beginning of GSI process, where shorter lengths (60ms), shown relatively high global values when compared to longer lengths (100 and 260ms). It is also noticed that in particular, for RW wavelets extracted with $T$ of 2500ms had generate slightly higher global correlation values when compared to its equivalent CP wavelet, under same $L$ of 100ms and using all available wells. Wavelets estimated by different well sets generated different global correlations depending of wavelet extraction method and seismic window. The less reliable CP wavelet (extracted using $T$ of 2500ms, $L$ of 100ms and wells from group 2) characterized by an asymmetry in main loop (Figure 1 and 2) was the one with lowest global correlation.

![Wavelets scenarios selected to perform GSI and corresponding RW wavelets estimated phase error (in degrees). Wells A-01, A-02 and A-04 are denominated as group 1 while wells A-03 and A-05, group2.](image)

![Global correlation achieved for each wavelet scenario. Green colors are related to STAT wavelets, blue to CP and orange colors related to RW.](image)
When analysed the local correlation between all seismic traces, for each scenario, wavelets extracted using the largest seismic window show at same time the lowest and higher variability of local correlation, depending on the method and selected wells (Figure 3a). Related to used method, wavelets extracted using CP method show a more scatter behaviour and are more affected when considered larger T, while RW method showed the lowest dispersion of local correlation (Figure 3b), with the one extracted under the largest T characterized by least dispersion of local correlation.

Figure 3: Local correlation standard deviation values, for all seismic traces classified by a) seismic window (T) and b) method of extraction.

Original distribution function and spatial continuity patterns were honoured by most of resulting best-fit Ip models. Best-fit Ip model originated by the less reliable wavelet, with lower global correlation was able to reproduce more the original spatial continuity and distribution function than the one that result from RW wavelet with longest wavelet length which result in more distinct character (Figure 4).

Multidimensional scaling (MDS)

The purpose of using the MDS is to quantify dissimilarities between models represented as unique points in MDS plots, and it was used to assess and quantify uncertainties between the resulting acoustic impedance models obtained by GSI inversion under different wavelet scenarios.

Bandwidth of seismic data controls vertical resolution and if used, during the GSI inversion, wavelets characterized by a time response that is reflecting a gap of seismic bandwidth (main wavelet loop poorly defined) the resulting synthetic seismic is going to struggle to replicate the original recorded seismic generating lower global and local correlation values. The corresponding generated best-fit Ip models is characterized as high uncertain, not reflecting the real subsurface physical properties and leading to incorrect estimations. This was proved by using an unreliable CP wavelet and at MDS plot this model was characterised has the most dissimilar one (Figure 5). Statistical wavelets (with different seismic windows and same adequate wavelet
length) are clearly generating models not showing high similarities between them and define the approximate limit of the well-defined cluster area (Figure 5a), reflecting an average behaviour of these resulting best-fit models. Models that result from wavelets estimated using CP method, are more spread-out reflecting more dissimilarities. From the selected RW wavelets scenarios it is observed that they are all inside the cluster area and consequently showing more similarities between them. It must be taken in consideration that best-fit Ip model that result from RW wavelet with long length, even showing similarities in MDS space to other best-fit models, was characterized by a higher spatial continuity than the original one and was generated by the wavelet one with higher phase error (around 14°). In MDS plot there are overlapped best-fit Ip models, originated from wavelets that are independent of method of extraction and parametrization used (Figure 5b).

**Assessment of wavelet length**

At this stage it is possible to infer that a long wavelet estimated by RW method, is potentially compromising the reproduction of the original distribution function and spatial continuity, while using it in the GSI methodology, although with high values of global and local correlations. This wavelet is over-fitted to the seismic data incorporating more noise to it and generating a smoother acoustic model with longer spatial continuities and more homogenous features. It is clear that seismic noise uncertainties are not reflected in the assessed uncertainty since it is considered as been part of the signal. Trying to understand if long CP wavelets would behave similarly to its equivalent RW, it was performed an additional GSI inversion, where the average global correlation, achieved in last iteration was 0.74, around 10% below the maximum global value (0.92) and of 15% below their equivalent RW wavelet (Figure 5). Related to local correlation, when considered all seismic traces, the generated best-fit Ip model had the second highest variability and lowest mean local correlation value from CP's group, after the CP wavelet with T of 2500ms L of 100ms and using wells from group 2 (Figure 6).

For this particular long CP wavelet, Ip models generated in last iteration had the second highest standard deviation values (Figure 7) after the generated by the CP wavelet extracted using T of 2500ms, L of 100ms using wells from group 2, reflecting higher uncertainties than models generated the by the equivalent RW wavelet, that have the lowest standard deviation values. From the upper quartile value, it is possible to identify that the models with higher uncertainties are more associated to models that result from CP wavelets.
and to statistical wavelet extracted using the larger seismic window. It is also observed that models generated by statistical wavelets have median variances in general.

**Final remarks**

After all the accomplished analysis some remarks can be done: first, the used wavelet must be reliable and selected parametrization need to be consistent and in accordance with main objectives and data set, otherwise they will contribute highly to the model’s uncertainties. Second, both global and local correlation values are going to be affected by the use of wavelets with different uncertainties associated. Third, with MDS plots it is possible to identify the similarities between best-fit acoustic impedance models and understand how real subsurface properties are being explored under different wavelet scenarios. Their individual uncertainties are reflected in the resulting acoustic models with higher impact for wavelets extracted with Constant Phase, while Statistical wavelets are reflecting a mean behaviour around the cluster area and Roy White generate more similar models. When considered the stationarity assumption related to phase, while estimating a representative wavelet, and in accordance to main inversion interval objectives, longer lengths wavelets generate Ip models with distinct behaviours, depending of the used method of extraction. Long RW wavelet generated smooth best-fit Ip model that compromise the reproduction of the original spatial continuity and distribution function, although associated to lower uncertainties. In contrary, using the equivalent CP wavelet, the resulting best-fit Ip model is honouring more the original spatial continuity and distribution function, and characterized by higher uncertainties.

5. **Conclusions and Recommendations**

Any seismic inversion uses both seismic and well data as inputs, and being the link between them a wavelet, it is important to use one that should be the most reliable and adequate to achieve main inversion goals, and their uncertainties throughout the estimation process not impact negatively in the task of real subsurface parameters exploration. GSI inversion methodology together with MDS prove to be a powerful tool to assess and quantify the uncertainties associated to generated models under different wavelet scenarios, with different uncertainties associated, and understand how the
real parameters space are being explored. When used unreliable wavelets, in particular for the extracted using the Constant Phase method, the generated synthetic data struggled to reproduce the recorded seismic data, resulting in high uncertain models, impairing the ability to explore the real model parameter space. Best-fit acoustic impedance models that result from wavelets extracted using Roy White method are more similar and with lower uncertainties even if considered an unreliable wavelet scenario. Statistical wavelets, estimated base on seismic data, generate best-fit models that are reflecting a mean behavior of real parameter's characteristics.

It is recommended the use of different partial stack seismic data to estimate preferable wavelet scenarios in agreement to the ones already tested in GSI and evaluate their impact GEI inversion elastic models. In addition, quantify uncertainties with MDS tool modelled using kernel techniques, with purpose of identify patterns, which are not possible to be identify with the traditional MDS methodology. Define the most adequate wavelet to perform future and more complex seismic inversion to this particular data set and objective.

6. References


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