Seismic Inversion of under-sampled reservoirs

Torres Astrid[1]; Soares Amilcar[1]; Nunes Ruben[1]; Cersosimo Sergio [2]; Leggett Miles[2]

[1]Instituto Superior Tecnico, Centre for Petroleum Reservoir Modelling, Lisbon, Portugal
[2]Galp Energia, Lisbon, Portugal

ABSTRACT

Seismic inversion of under-sampled reservoirs at early exploration stages is still a research challenge, given the lack, or total absence, of data for the inversion: acoustic impedance distributions, wavelet etc. In this study the available information is a 2D seismic line, the final section of interval velocity obtained from processing and seismic horizons resulting from the interpretation. No well information is available in the area of study.

In this project two different approaches of seismic inversion are performed: a deterministic, given by a model-based inversion and a stochastic executed following a global stochastic inversion methodology. Because of the absence of well information, two pseudo-logs of acoustics impedance were generated: i) by extraction of a trace from the interval velocity section and using Gardner's relationship to calculate the density and then per-forming the calculations of the acoustic impedance, ii) by extraction of a trace from the result of the deterministic inversion.

The initial model used in the model based inversion was generating by the interpolation of the first pseudo-log and taking into consideration the seismic interpretation.

Global Stochastic Inversion was executed considering three cases: 1) using the second pseudo-log and as low frequency model the initial model used in the model-based inversion, 2) using a model of geological zones and conditioning the GSI to the local acoustic impedance distributions taken from the second pseudo-log, 3) using as input the output from the deterministic inversion and performing the simulations and co-simulations with direct sequential simulation with local variable means.

The results show that the technique allow us to explore different scenarios regarding the spatial distribution of acoustic impedances and assessing the corresponding uncertainty of them. Another important issue addressed in this application is about the quality of seismic data: in zones where the quality of the seismic data is doubtful the variability of final acoustic impedances images is high, which mean that this are poorly matched at the end of the inversion process, do not forcing the inversion to reproduce the seismic in the area and therefore not reproducing the noise in the final result. The advantage of this seismic inversion technique is that do not need log data in the area to be inverted, being possible to use logs from other places with a similar geology, this make of this technique suitable for under-sampled reservoirs.

Keywords: Seismic inversion, acoustic impedance, deterministic inversion, stochastic inversion, model-based inversion, global stochastic inversion

INTRODUCTION

The Seismic reflection method represents one of most important tools in hydrocarbon exploration, because it has a great power of resolution and penetration. In this method, a seismic artificial stimulus, given by a seismic wave, is induced into the subsurface and then the travel time of the wavelet from its generation until its reception is measured using recording equipment placed on the surface. Therefore with the travel times and estimation of the velocity of propagation it is possible to do a reconstruction of the trajectories of seismic waves. The travel time depends on factors such as the physical properties of the rocks, the structural geology of the area and the fluid content.

In Geophysics the direct problem is known as forward or simulation problem, which according to Tarantola (2005), is defined as the prediction of the outcomes of measurements, given a complete description of a physical system. The inversion problem is the opposite process and allows the trans-formation of seismic data into quantitative properties of rocks, contributing to the description of the quality of a reservoir, which means that this technique now has an important role in the characterization of reservoirs. In early stages of exploration the use of the seismic inversion process could be limited by the lack of available data, motivating the development of new methodologies in the application of this technique.

Acoustic impedance is a defined as the product between the P-wave velocity and the density of rocks and is related to the lithology, rock compaction and existence of fluids in the rock, which makes this property one of the most useful physical properties in reservoir characterization. In the inversion initially a log calculated by multiplying density and sonic log is generated. Nevertheless, in the absence of well data, it is possible to generate a pseudo-log by combining the Dix equation to convert the RMS velocity to interval velocity and Gardner's equation to calculate the density.

There are two different approaches to seismic inversion: deterministic and stochastic. According to Francis (2005) deterministic inversion is based on the minimization of an error term between the forward convolution of the reflectivity from an estimated impedance profile and the seismic input data. In each iteration the model is perturbed until a difference close to zero is obtained. There are different methods used to perform the deterministic inversion of acoustic impedance in post-stack data, for example, the classical recursive or band limited, sparse-spike and model-based.

According Russell and Hampson (1991), model-based inversion starts with an initial model, which is adjusted until the synthetic seismic section best fits the acquired seismic data and therefore the error, given by the difference between the synthetic section and the seismic data, is minimized. According to Simm and Bacon (2014) the starting model could be an interpolation of well data (probably with a low-pass filter applied), a general trend model based on geological model knowledge or the seismic stacking velocity cube. The advantage of deterministic approaches is the short computation time.

For the stochastic inversion there are two different approaches: The Bayesian algorithms (e.g. Buland and Omre 2003; Buland and El Ouair 2006; Grana and Della Rossa 2010) and the geostatistical inversion algorithms (e.g. Mallick 1995; Mallick 1999; Boschetti, Dentith, and List 1996; Amilcar Soares, Diet, and Guerreiro 2007). Both are optimization processes to solve the inverse problem of the petrophysical parameters, knowing the seismic data. According to Azevedo (2012), the stochastic inversion generates equiprobable outputs of petro-physical properties, such as acoustic impedance, with the main objective to quantify the uncertainty of these properties. The initial model of each realization is obtained through stochastic simulation conditioned to well data and models of the spatial distribution. The average of the equiprobable solutions is defined as the expected value of the given variable. In this approach N iterations are performed, until the correlation coefficient reaches the desired value. In summary, this method aims to minimize the differences between the synthetic seismic traces designated by convolution with the wavelet, and the actual seismic. Once the equiprobable results are obtained, they can be statically analyzed to calculate the variance and to estimate uncertainties and probabilities.

One of the methodologies used in stochastic inversion is the trace by trace methodology, which according to Soares et al. (2007), performs a sequential approach in two steps: first, the acoustic impedance values are simulated for one trace based on well data and information about the spatial continuity given by the variograms, therefore for each simulated trace a synthetic seismogram is generated by using the convolutional model of the seismic trace and compared with the real seismic data. The simulated traces that have a better match with the real seismic are retained and another trace is simulated and transformed. The process continues until all the traces of acoustic impedance are simulated as "real" data for the next sequential simulation step

A new methodology proposed by Soares et al. (2007) is Global Stochastic Inversion (GSI), which is based on two key ideas: the use of the sequential direct co-simulation as the method of "transforming" images, in an iterative process and to follow the sequential procedure of a genetic algorithm optimization to converge the transformed images towards an objective function. This methodology follows a different approach compared to the trace by trace methodologies, because several realization of the entire seismic information of acoustic impedance are simulated instead of individual traces, then a synthetic seismic is calculated for all the simulated images of acoustic impedance and compared with the real data; areas of best fit of different images are selected and a new image is built with the merged information, which is going to be co-simulated in the next iteration. This process is iteratively repeated until obtain a minimum to reach an objective function. At the end are generated images of the merged of best correlation values and the acoustic impedance values associated to them.

The aim of this project is to explore a hybrid approach by coupling the advantage of deterministic inversion, given by a model-based inversion and a stochastic methodology executed following the geostatistical method, represented by the Global Stochastic Inversion. The available data is a 2D seismic section, which was previously processed to be used in this project, the interval velocity section from processing and interpreted seismic horizons.

In this project the Global Stochastic Inversion technique was performed, following three different new approaches, where the difference between them are in the input data and the calculation of local means in the simulation stages.

Case1. Using as input a soft-model generated for the execution of the model-based inversion. In the simulation stage is considered a direct sequential simulation using a simple kriging with local means, where the local means are set by the input image.

Case 2, conditioning the GSI with local models of parameters, probability distribution functions and local spatial continuity models (variograms).These models are defined in zones according to the geological interpretation, grouping layers with a similar behavior in the properties. The simulations are performed with a direct sequential simulation using local distributions and local models of variograms of AI. In this case the input for the simulation of the first iteration the same initial soft-model used in the model-based inversion.

Case 3. Using as input the output from the deterministic inversion. In this case the simulations and the co-simulations are performed using a direct sequential simulation with a simple kriging with local means for the first iteration and after the first iteration using a collocated co-kriging with locally variable mean, where the best section is used as secondary variable and the result obtained in the deterministic approach is used as image of local means.

METHODOLOGY

In figures 1 and 2 is shown the available data for this study, the final stack of a 2D line with the horizons provided by the interpreter and the final interval velocity section from seismic processing. As was mentioned before for this project no well information is available. The data consists of a 2D line with 5194 CDP's with a sampling rate is 4 ms.

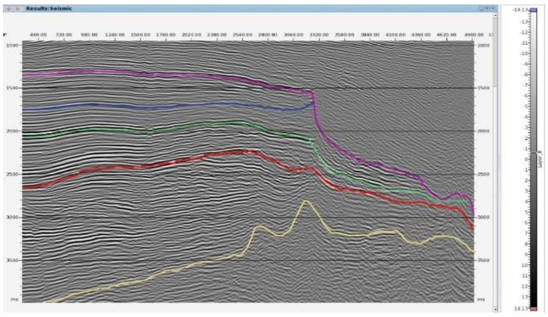

Figure 1. Final PSTM from processing (interpreted)

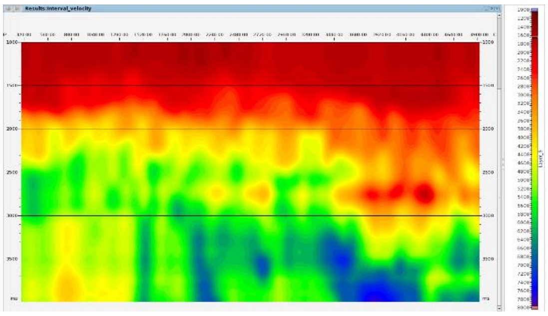

Figure 2. Final interval velocity section

Model-based Inversion

This inversion was performed using Strata, which is a software widely used in the industry, developed by CGG Hampson-Russell. This type of inversion needs as input the seismic data, a wavelet, interpreted horizons and well logs. The software has the option to extract a statistical wavelet from seismic, in this case a wavelet with a length of 200 ms and minimum phase was extracted, taking into consideration the final phase of the seismic processing. In Figure 3 can be observe the extracted wavelet used for the inversion.

As was mentioned before in this case well data was not available, for that reason it was necessary to create pseudo logs of P-wave velocity and density, which are a requirement of the software. The P-wave velocity log was obtained by the extraction of a trace from the section of interval velocity and the density log was calculated using the Gardner relationship. After calculating the pseudo logs for P-wave velocity and density, it is possible to generate a pseudo log for acoustic impedance, which is going to be used in the inversion process. Figure 4 shows the initial pseudo-log for acoustic impedance, which has values from 10547 (m/s)*(g/cc) to 17319 (m/s)*(g/cc).

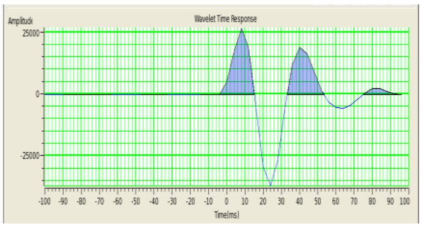

Figure 3. Extracted wavelet

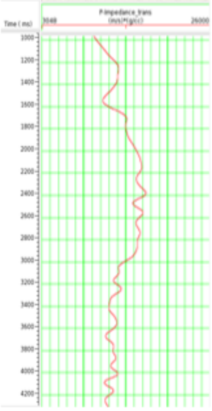

Figure 4. Initial pseudo-log for acoustic impedance

This inversion has as an input an initial model, which should reflect the geological structure of the area and has an approximation to the real values of the property. Usually, it is created by interpolating the values of the well data of the property to invert; this interpolation is guided by the interpreted horizons. The well data has a higher resolution compared with the seismic data and applying a low pass filter, permitting a maximum frequency between 10 and 15 Hz, generating then a low frequency model. In this case due to the absence of data, the initial model was generated by extrapolating the values of the pseudo-log of acoustic impedance and taking into consideration the horizons previously interpreted; this data is already low frequency and for that reason it was not necessary to apply a high-cut filter in the model. Figure 5 shows the initial model of the inversion.

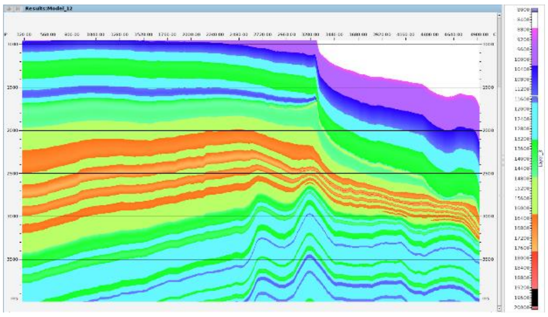

Figure 5. Initial model of the model-based inversion

Global Stochastic Inversion

The Global Stochastic Inversion was performed using a computational code which is currently being developed in the CERENA at the Instituto Superior Tecnico. It is important to mention that this inversion is more flexible than the Model-based inversion, because it has as advantage that it does not need log data in the survey and it is possible to use logs from other places in the area a similar geology and making use of this technique suitable for under-sampled reservoirs.

In the inversion process was used the wavelet shown before, but a new pseudo-log for acoustic impedance was used, which was generated by extracting a trace from the result of the model-based inversion, in order to have a new pseudo-log with the contribution of the seismic. Figure 6 shows the pseudo-log of P-wave impedance used in the inversion process, which has values from 8932 (m/s)*(g/cc) to 26769 (m/s)*(g/cc).

To establish a quantitative measure of the spatial correlation a spatial analysis was performed. In this stage were calculated the experimental variograms, for the seismic and for the well data. After the calculation, these variograms were adjusted to theoretical models. Due the data limitation only two directions were considered, the vertical with azimuth= 0º and dip=90º and the horizontal direction with azimuth =90º and dip= 0º. The variogram in the vertical direction was calculated from the well data and the variogram in the horizontal direction from the seismic data. In table 1 are the parameters used to model the variograms and the variograms calculated and the adjustment to a theoretical model are shown in the figures 7 and 8.

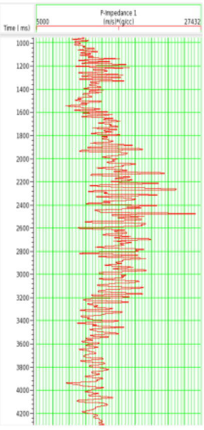

Figure 6. Pseudo-log for acoustic impedance used in the GSI

Angle	Amplitude	Sill
(0,90)	22 ms	4759085
(90,0)	1250 m	32

Table 1. Parameters used in the variogram modeling

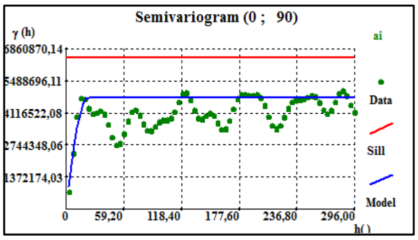

Figure 7. Vertical variogram (Green filled circles) and modeled variograms for the input data (blue line).

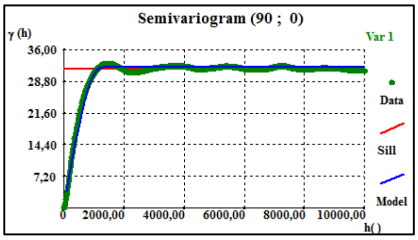

Figure 8. Horizontal variogram (Green filled circles) and modeled variograms for the input data (blue line)

It is important to mention that in both variograms the adjustment was performed with a spherical model, which is commonly encountered in the model in geostatistics. For the vertical variogram it is possible to observe a cyclical behavior in the variogram that could be related with variations in the lithology in the vertical axis, which in this case is in milliseconds

RESULTS

Model-based Inversion

Figure 9 shows the result obtained in the model-based inversion, where is evident that exists a correspondence in the trend of the values of acoustic impedance compared with the initial model (figure 5).

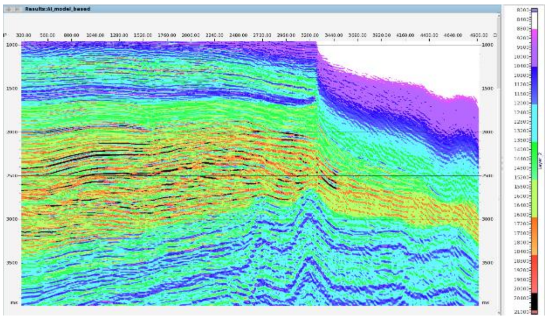

Figure 9. Model-based Inversion result

In this result is also obvious the influence of the seismic, reproducing inclusive the noise present in it, which is expecting because this type of inversion tries to match the inverted model and the seismic events in places even with a low signal-noise ratio. This could be mitigate with more constrain to the input low-frequency model, but in this case taking into consideration that this model was generated only with one pseudo-well, was decided to have an equal contribution of the model and the seismic.

Global Stochastic Inversion

Case1. GSI with the input used in the Model-based Inversion as local trend

The result obtained in the GSI using as input the input model used in the deterministic approach (figure 5) is shown in figure 10, where could be observed that the result has a seismic behavior, but with a better attenuation of the noise compared to the result obtained for the model-based inversion. It is also evident that the inversion result has a correspondence with the input model and therefore the model is being respected, however this correspondence is less evident than in the result obtained for the model based inversion.

The GIS has the capability to calculate and reproduce as outputs the synthetic seismic sections calculated in each simulation. Figure 11 shows the synthetic obtained for one simulation of the last iteration, in which is possible to observe that the main structure is reproduced and in some areas (between 1.5 and 2 seconds) the reflectors have been enhanced. In areas where the signal-noise ratio is low (between 1 and 1.5 second and CDP's 3800-4900) the synthetic has information, nevertheless is not coherent and has not correlation with the input data (figure 1). It is also evident that there is a difference in the relative amplitudes between the reflectors compared to the input data, which was not observed in the synthetic calculated in the model-based inversion, in which the software as part of the inversion procedure applies a scaling to the amplitude of the synthetic.

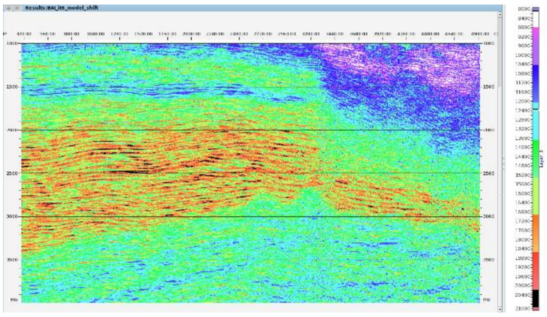
Figure 10. Best acoustic impedance section obtained in case 1

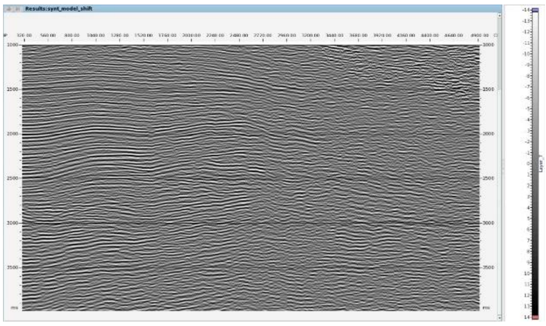
Figure 11. Synthetic calculated in case 1

Another characteristic of GSI is the reproduction of spatial continuity pattern of acoustic impedance as they are revealed by the variogram. As a quality control of the result, the horizontal and vertical variograms were calculated. The vertical variogram (figure 26) was calculated extracting a trace of the best acoustic impedance section and the horizontal variogram was calculated from the synthetic shown before (figure 11). The parameters used to model the variograms are shown in table 2. For both variogram were obtained the same values of the amplitude shown in the past chapter for the well log data (figure 15) and the input seismic (figure 16), which means that the spatial continuity of the variable is reproduced. The maximum variance for both variogram is different that the values shown before. For the vertical variogram, it is also possibly to observe a cyclic behavior, similar to that observed in the variogram performed for the well log data.

Angle	Amplitude	Sill
(0,90)	22 ms	3119375
(90,0)	1250 m	39

Table 2. Parameters used in the variogram modeling for the result of case 1

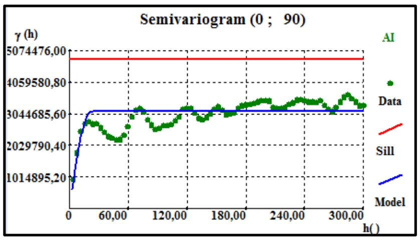

Figure 12. Vertical variogram (Green filled circles) and modeled variograms (blue line) calculated for the result of case 1

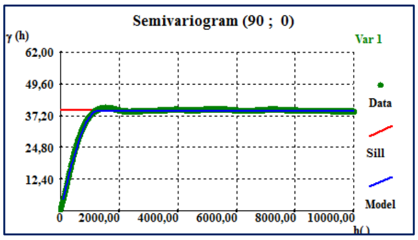

Figure 13. Horizontal variogram (Green filled circles) and modeled variograms (blue line) calculated for the result of case 1

One of the outputs of GSI is the best correlation section for each iterations. In this case figure 14 shows the best correlation section for iteration 6, which has values between 0.14 and 0.99, with a mean value of 0.91.The low values in the correlation (red colors in figure 14) are in zones where the seismic input data has low quality and the synthetic shown before (figure 11) has a bad definition of seismic events.

The variance for all the simulations of the last iteration was calculated and is shown in figure 15, where it is possible to observe that the variance has the highest values in zones where the seismic quality is poor, being related with those areas where the synthetic has problem in the definition of the seismic events.

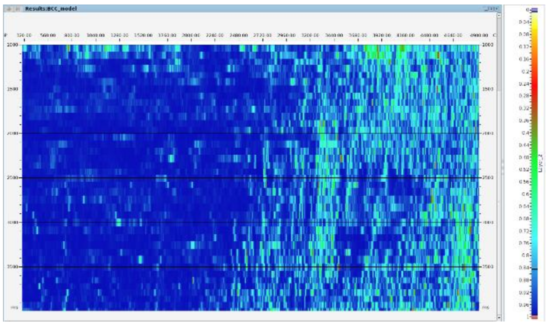

Figure 14. Best correlation section for case 1

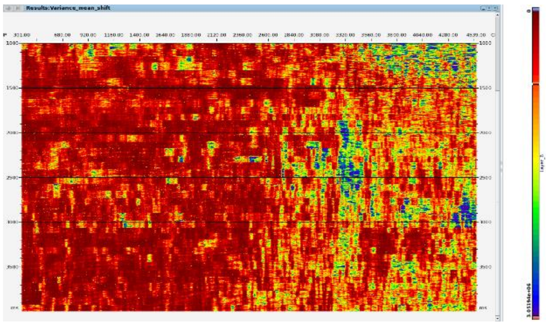

Figure 15. Variance calculated for case 1

Case 2: Using a model divided by zones according to the geological interpretation

In this case the study area was divided in in 6 zones identified in figure 16. It is important to mention that it is also necessary to divide the pseudo-log and for each zone must be input the maximum and minimum values of the property in the range (table 4).

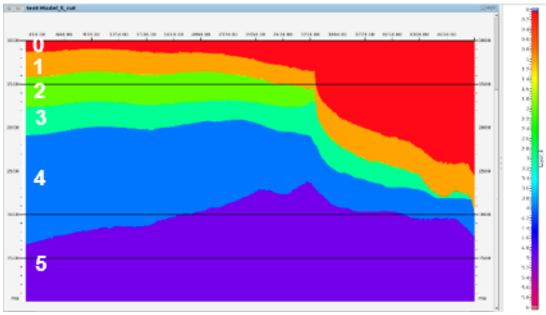

Figure 16. Model of zones used as input in the GSI

Zone	Minimum	Maximum
0	10156	13376
1	10364	17723
2	8939	16940
3	10868	19532
4	10689	26769
5	9063	20042

Table 4. Minimum and maximum values of the pseudo-well for each zone (Values are in (m/s)*(g/cc))

Figure 17, shows the result obtained after to execute the GSI with the initial model shown before (figure 5), where it is possible to observe that due to the lateral changes in the property was hard to estimate values in some areas, as for example in the zone 0 the result looks homogeneous and it is not possible to distinguish the changes observed in the results shown before for the deterministic approach (figure 9) and in case 1 (figure 10).

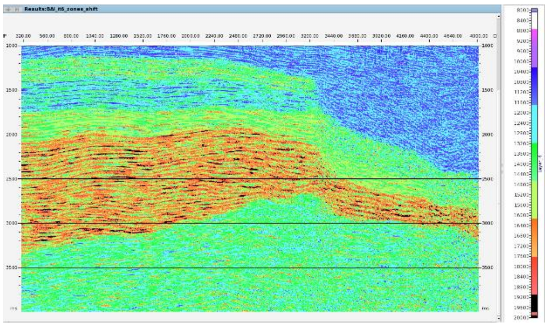

Figure 17. Best acoustic impedance section obtained in case 2

In the synthetic calculated from one simulation (figure 18), it is evident the contrast between the first two zones of the model and the lack of seismic information in the first zone. Regarding the main structure is observed the same phenomena pointed out for case 1, this has a bad definition in zones where the data has a poor quality.

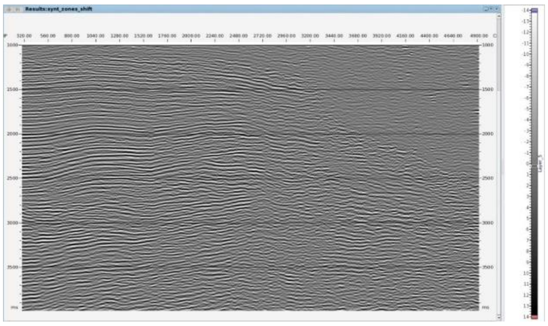

Figure 18. Synthetic calculated in case 2

Angle	Amplitude	Sill
(0,90)	22 ms	2622657
(90,0)	1250 m	31

Table 3. Parameters used in the variogram modeling for the result of case 2.

Table 3 shows the parameters used to model the calculated variograms (figures 19 and 20), which show the same value in the amplitude that the input variograms (figures 7 and 8), meaning that the spatial continuity of the variable is being reproduced. The maximum variance for the horizontal variogram is close to the maximum variance of the seismic data, but in case of the vertical variance has an important difference.

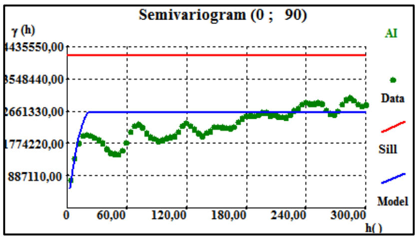

Figure 19. Vertical variogram (Green filled circles) and modeled variograms (blue line) calculated for the result of case 2.

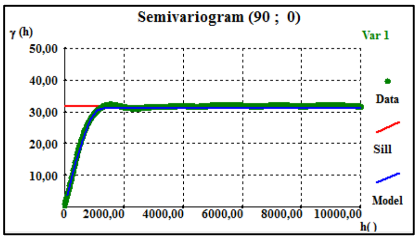

Figure 20. Horizontal variogram (Green filled circles) and modeled variograms (blue line) calculated for the result of case 2.

Figure 21 shows the best correlation section obtained for this case, which has values between 0 and 0.99, with a mean value of 0.91. In this figure it is possible to observe that the lower values of correlation are in areas where the synthetic has problems to define the reflectors, which are areas where the quality of the data is poor.

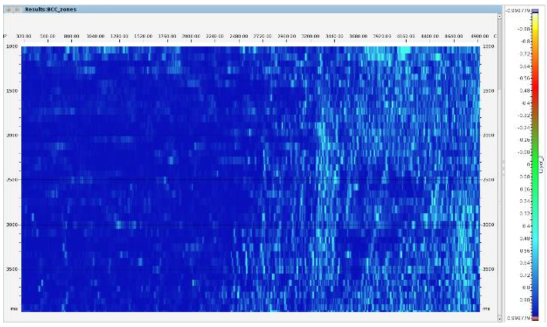

Figure 21. Best correlation section for case 2

Figure 22 represents the variance calculated for this case, where it is evident the contrast between the zone 0 (figure 16) and the others zones; zone 0 has a low variance because has a low variability between the values and the minimum a maximum values of the input histogram are close. The variance is high in areas where in the synthetic did not define the seismic reflectors and where the synthetic pseudo-log has a strong difference with the values of the input model used in the inversion.

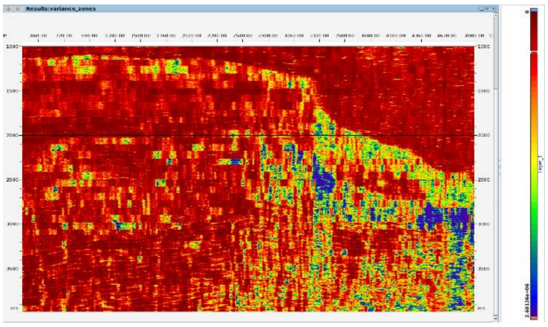

Figure 22. Variance calculated for case 2.

Case3: Using the output from the deterministic inversion

Figure 23 shows the result of the GSI using the output of the deterministic inversion (figure 19) as local trend. It is possible to observe that the dipping noise existing in the seismic after 3000ms is attenuated, also that the result compared with the input looks less synthetic and the initial model influence is not so strong. In this case the maximum and minimum values were fixed by the input.

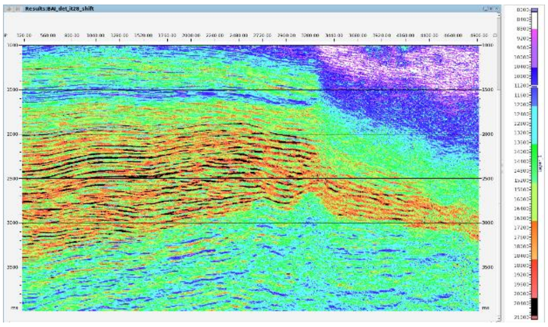

Figure 23. Best acoustic impedance section obtained in case 3

The synthetic calculated for case 3 is in figure 24, where is possible to observe that in general there is a good match with the input seismic (figure 1), with an exception in noisy areas. Comparing the synthetic calculated for this case with the synthetics calculated for case 1 and case 2, this has higher amplitudes and therefore stronger reflectors, which could be given by the fact that in this case the input has more variability and a bigger range of values.

Figures 25 and 26 represent the vertical and horizontal variograms and table 5 the parameters used to model them. The value for the amplitude in both cases is equal to the values calculated for the well log and the input seismic data (figures 7 and 8), also the shape in both cases is similar, however, there is a variation in the sill which in both cases is higher than the sill of the input data, this could be related with the fact that the input data for this case has a high variability in both directions.

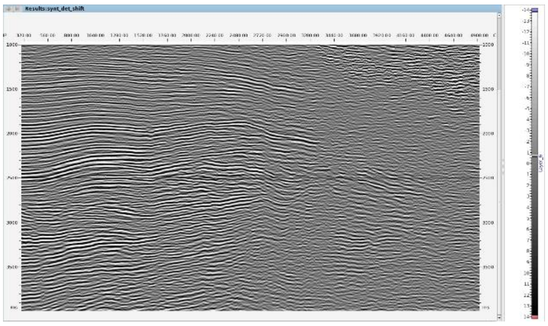

Figure 24. Synthetic calculated in case 3.

Angle	Amplitude	Sill
(0,90)	22 ms	5779468
(90,0)	1250 m	59

Table 5. Parameters used in the variogram modeling for the result of case 3

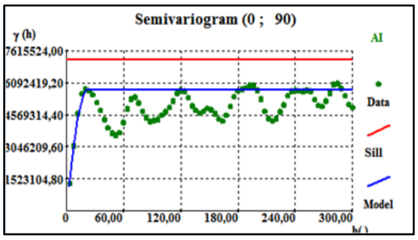

Figure 25. Vertical variogram (Green filled circles) and modeled variograms (blue line) calculated for the result of case 3

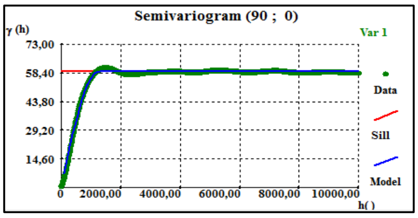

Figure 26. Horizontal variogram (Green filled circles) and modeled variograms (blue line calculated for the result of case 3

The best correlation section calculated in the inversion is in figure 27, which has a minimum value of 0 and a maximum value of 0.99, with a mean value of 0.93. The correlation is lower in noisy areas, where in the synthetic (figure 24) are observed problems in the definition of reflectors.

Figure 28 represents the variance calculated taking into consideration the 32 simulation of the last iteration, which is high in areas where the seismic information has a low signal-noise ratio and the synthetic calculated during the inversion has a poor definition of the events. Also the variance is high in zones where the main structure has an important lateral change.

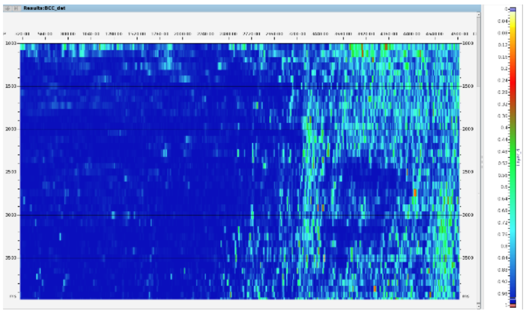

Figure 27. Best correlation section for case 3

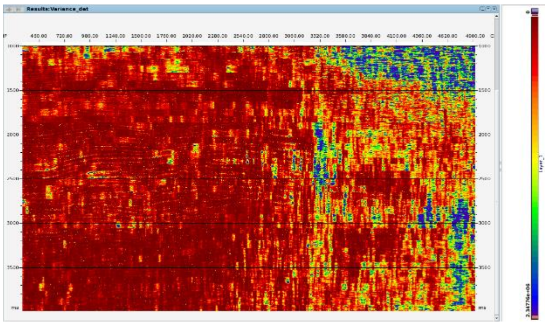

Figure 28. Variance calculated for case 3

CONCLUSIONS

The final results have shown that the Global Stochastic Inversion for acoustic impedance is a suitable technique to be apply in reservoirs in total absence of well data and makes possible an assessment of the uncertainty given by the calculation of the best correlation section and the variance of the simulations.

The new approach proposed in this study by integrating the result of a fast deterministic inversion as prior image of acoustic impedance in the Global Stochastic Inversion has shown a promising result and can be considered as a valid alternative to perform seismic inversion in under-sampled reservoirs.

The use of local models in the Global Stochastic Inversion shown that this approach is also a promising technique when the geological knowledge is sufficient.

The variance in all the cases studied gave high values in areas where the quality of the seismic data is reduced. In those areas lower values of correlation were obtained, which means that at the end of the inversion process those remain poorly matched.

The result of the model-based inversion reproduces the seismic data and also the noise in it. This could represent a problem when the data has poor quality, because create artifacts in the inverted section. Nevertheless, this methodology shown to be useful to generated pseudo-logs of acoustic impedance that reflect the vertical variability of the property.

Variograms for the best acoustic sections were performed, which revealed that the technique is reproducing the spatial continuity of the data. However, calculated values for the sill in all the cases were very different to the sill of the variograms calculated for the input data, which means that the level of variability of the property is not being reproduced, this is more evident for the vertical variograms.

In order to obtain a better image of best acoustic impedance in case 2, it is recommended to perform the flattening of the data to avoid the miscalculation in places where the structure generates important lateral changes in the value of the property.

It is also recommended to use the deterministic inversion to generate one pseudo-log in each trace in order to have a better estimation of the property in all the areas, this could help to have a better estimation due to the lateral variation of the property.

Combing a deterministic approach and a stochastic approach to perform the inversion of acoustic impedance shown to be a suitable solution for the limitation of quantity and quality of the data in under-sampled reservoirs.

REFERENCES

Azevedo, L., Nunes, R., Almeida J. Caeiro M., Correia, J. and Soares, A. (2012). Seismic Attributes for Constraining Geostatistical Seismic Inversion. Ninth International Geostatistics Congress.

Boschetti, F., Dentith, M.C, and List, R. D. (1996). Inversion of Seismic Refraction Data Using Genetic Algorithms. Geophysics, 61, 1715–1727. doi:10.1190/1.1444089.

Buland, A., and El Ouair, Y. 2006. “Bayesian Time-Lapse Inversion.” Geophysics, 71, R43–R48. doi:10.1190/1.2196874.

Buland, A., and More, H. 2003. “Bayesian Linearized AVO Inversion.” Geophysics, 68, 185–198.

Francis A. (2005). Limitations of Deterministic and Advantages of Stochastic Seismic Inversion.

Grana, D., and Della Rossa, E. 2010. “Probabilistic Petrophysical-Properties Estimation Integrating Statistical Rock Physics with Seismic Inversion.” Geophysics, 75, O21–O37 doi:10.1190/1.3386676.

Mallick, Subhashis. (1995). Model Based Inversion of Amplitude Variations with Offset Data Using a Genetic Algorithm. Geophysics 60, 939–954. doi:10.1190/1.1443860.

Mallick, Subhashis. (1999). Some Practical Aspects of Prestack Waveform Inversion Using a Genetic Algorithm: An Example from the East Texas Woodbine Gas Sand. Geophysics 64, 326–336.

Russell, B., and Hampson D. (1991), Comparison of post-stack inversion methods: 61St Annual International Meeting, SEG, Expanded Abstracts, 10, 876-878.

Simm R. and Bacon M. (2014). Seismic Interpretation Handbook. Cambridge University Press.

Soares, A., Diet, J.D., and Guerreiro, L. (2007). Stochastic Inversion with a Global Perturbation Method. Petroleum Geostatistics, EAGE, Cascais, Portugal (September 2007), 10–14.

Tarantola A. (2005). Inverse Problem Theory. SIAM