Geostatistical Seismic Inversion of the Arruda Sub-Basin, Portugal

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Abstract:
With the increasing complexity of hydrocarbons reservoirs there is a constant need of combining different kinds of information, such as geological (e.g. basin characterization, main petroleum systems, structural and geodynamic history, stratigraphical units and main paleoenviroments), seismic reflection data (e.g. seismic interpretation and seismic inversion), well logging, (e.g.petrophysical properties and formation evaluation) and geostatistical modeling to characterize the spatial distribution of the subsurface properties of interest in order to provide the best insight for an unexplored area.

This thesis consists on the evaluation of a portion of the Arruda sub-basin from the Lusitanian Basin, Portugal, with the integrated interpretation of: geological data, seismic interpretation of two 2D seismic lines, interpretation of the well logs from the well Benfeito-1, and finally the inference of the subsurface elastic properties recurring to a geostatistical seismic inversion.

This work aims to provide an exploration assessment for the regional geology in the Arruda Sub-basin from the Lusitanian Basin, Portugal, for its hydrocarbon potential.This goal is achieved with a new re-interpretation of the available 2D seismic reflection section and well-log data and, for the first time, the inference of subsurface elastic properties recurring to geostatistical seismic inversion.

One of the novel approaches of this work is the way geostatistical seismic inversion was used in an unexplored area with no well-log data to assess its potential in hydrocarbons. This is a different type of work from the ones published using geostatistical seismic methodologies, that are generally used for a large scale information 3D seismic cube, with well-log data from at least a few number of wells.

Keywords: Geostatistical Seismic Inversion for undersampled basins, Hydrocarbon Exploration, Arruda Sub-basin, Seismic Interpretation, Well-logging Evaluation.

Introduction

Over the years the Oil and Gas industry has been in constant change passing through highs and lows, producing from simple and huge onshore reservoirs to complex and very heterogeneous reservoirs from the deep offshore. Nowadays both exploration and production have become more complex and costly. Therefore, there has been huge efforts to improve the subsurface characterization of under-explored areas, or even to provide the best subsurface inference during production phases, minimizing the costs and consequently increasing the profit.

In early exploration cases with few data available, frequently with only seismic reflection and well-log data, geostatistical methodologies have proven to be a good solution to infer the subsurface properties of interest, both elastic and petrophysical while assessing the intrinsic spatial uncertainty of these properties.

Aims and Objectives

This study intends to contribute with a new understanding of the Arruda Sub-basin with a new re-interpretation of available seismic reflection and well-log and the inference of subsurface acoustic properties recurring to geostatistical seismic inversion.

It's also important to highlight that this work is a multi-disciplinary approach, a different type from the ones published so far for this study area, since it encompasses geostatistical seismic inversion for under-sampled basin with well-log data interpretation and seismic interpretation.

This thesis consists on the evaluation of a portion of the Arruda sub-basin, Portugal from the integrated interpretation of geological data, seismic interpretation of two 2D seismic lines, the interpretation of the well logs from the well Benfeito-1, and finally the inference of the subsurface elastic properties recurring to a geostatistical seismic inversion algorithm.

This work aims to provide an exploration assessment for the regional geology in the Arruda Sub-basin from the Lusitanian Basin, Portugal, in terms of its hydrocarbon potential.

Arruda Sub-Basin- Study Area

According to Kullberg et al. (2013), internally the Lusitanian basin can be divided in three sectors based on facies variations thickness of lithostratigraphic units, and tectonic boundaries, as can be seen on figure 2.

• Northern Sector (NBL), limited to the south by the fault of Nazaré, with a great thickness of sediments deposited during the Jurassic Lower - Middle and Upper Cretaceous.

• Central Sector (CLB), where the study area is, situated between failures of Nazaré in the north, and Torres Vedras-Montejunto – Arrife on the south, where the Jurassic Eastern has a strong thickness; corresponds roughly to the recharge area of current Estremadura Limestone Massif (MCE – Maciço Calcário Estremenho).

• Southern Sector (SLB) , bordered to the north by the failures Torres Vedras-Montejunto-Arrife and marked by the importance a high rate of sedimentation from the Upper Jurassic-Lower Cretaceous;

The Arruda sub-basin located on the CLB division of the Lusitanian Basin, corresponds to a half-graben developed during the Middle Oxfordian-Late Oxfordian as a consequence of transtensional rifting episodes that have affected the Estremadura Basin. This sub-basin represents an intra-continental pull-apart basin with a rhomb-like shape (Leinfelder & Wilson, 1989). Figure 1.

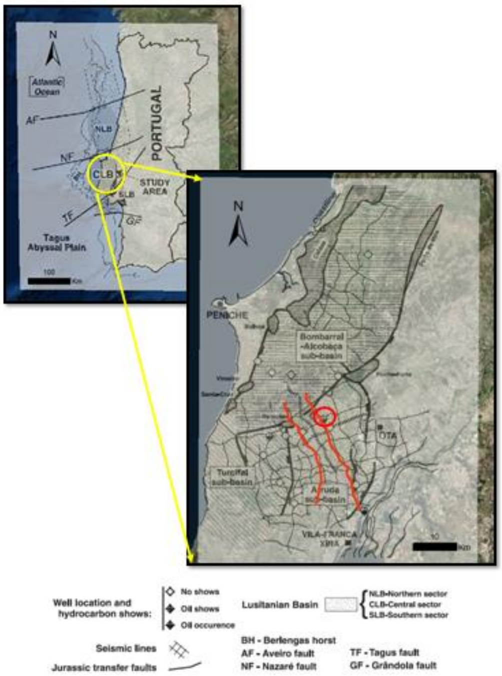

Figure 1 - The position of the Lusitanian Basin in Portugal today with its boundaries and offshore extension included. And the Central Lusitanian Basin where the study are is with detail, faults, diapiric structures, seismic lines and Benfeito-1 well from the data set. Adapted from Alves et al. (2003).

The litostratigrapich units of the study area belong to the Mesozoic Era, on Jurassic system period, and the basement belongs to the Triassic, they are mainly marly limestones, and silicilastic sediments, and a unit of salt, anhydrite, figure 2.

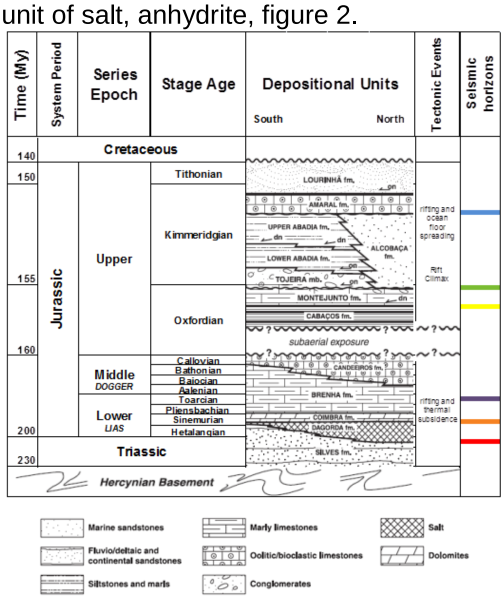

Figure 2 - – Summary of the Mesozoic lithostratigraphy of the southern part of the

Lusitanian Basin, and seismic horizons interpreted. Adapted from Alves et al, 2003.

Benfeito-1 Well Analyses and Petrophysics.

The Benfeito-1 well was drilled in 18 November 1982; the location is on Quinta da Boavista, on 750 m NW from the population of Parreiras. Was within a radius of 100 meters from the Seismic Line AR9-80_MIG, and the total depth of the well is 3343 meters.

The formations drilled along the well were 8 plus the total depth top, but in terms of seismic correlation, with the two 2D seismic lines of this data set, only 6 formations can be followed on the seismic reflectors, one of them corresponds to the basement,

They found indications of hydrocarbon on some of the stratigraphic units has reported on the Well Report , such as; Abadia Formation, Montejunto Formation, Dogger and Lias, at the depth of: 900-100m; 1270-1370m; 1500-1600m; 1750-2550m and 3094-3150m, they are identified with "stars", figure3.

In terms of well logging, the logs acquired started at 998 m of depth which correspond to the final part of the Abadia Formation. The main logs used to better understand the formations and characterized in a petrophysical way were; CALI, GR, Sonic DT, RHOB, NHPI, SP, SSP, MSF, LLD and ILD.

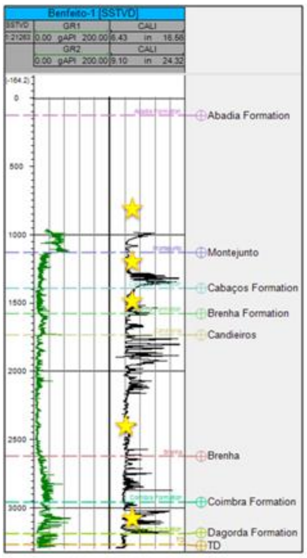

Figure 3 - Benfeito-1 Well Tops, and "reservoir" areas has "stars" on the report.

In order of the petrophysical data determined in this thesis, because the logs acquired started at 998 m of depth which correspond to the final part of the Abadia Formation, and ends at 3273m, which corresponds to a middle part of the Dagorda Formations, these two units can be analyzed on a representative and accurate way.

In terms of volume of shale, Candeeiros Formation is the one that present the lower value, due to the fact that is a dolomitic limestone. All the other formations present intercalations of shale and silty material increasing the value for the volume of shale. The Cabaços Formation is the formation with the lowest value of water saturation, 39.80%. The bulk density is directly related with the type of lithology, and the values are according to the lithologies present on each formation.

In case of porosity, the values correspond to the average value, calculated, for each unit individually. The porosities in these units are very low, this has been described on the well report for Benfeito-1, but if we look in detail, by plotting the sonic-log derived porosity versus the depth for each unit, we can infer some zones of interest with higher values of porosity.

For Montejunto Formation, which includes the Cabaços Formation as a member, at the top near 1137m depth have higher values of porosity (6-12%) comparing with the deeper part of the unit (Cabaços Member), between 1387m and 1585m, where the porosity values are around 2%. For Brenha Formation (Callovian) the values of porosity are more or less around 4% to 8%, and does not present a very distinct distribution along the depth. For Candeiros Formation the values of porosity present a very regular distribution along the depth, but the values vary between 0% to 4%. This lower values can be explained by the fact this formation has a oolitic and bioclastic component and in order of is size, that can decrease the values of porosity; and that's way this unit present the lowest value of porosity – 1,79%. For Brenha Formation (Aalenian-Pliensbachian; the values of porosity range between 2% to 6%, there is a tendency to present higher values in deeper areas, near the 2920 m. For the Coimbra Formation the values of porosity present better results on the top of the unit, (2963-3060m), around 2% to 4%, when compared to the lower part in depth that are very near 0%

Seismic Data Interpretation – Arruda Sub-basin

The data set analyzed in this thesis, is two 2D seismic (AR09_80-MIG and AR05_80-MIG), the coordinate system used is the ED-50 UTM, zone 29, referring to the zone were Portugal is.

The survey of this seismic was the PETROGAL 80, acquired during 1980-1981, with 35 lines, 2682 shot points and total length in km of 724,6.

For the seismic line AR09_80-MIG, see (Figure5), there is already some interpretations published by authors, but about the accuracy of that interpretations it's hard to make an argument, because some of the reflectors are very difficult to follow and the flower structure due to the movement of the salt, makes it even a more difficult to interpret, so there's no such thing has a the "right" interpretation for this line.

The seismic line AR05_80-MIG, see (Figure 5) was a challenge, the flower structure part is very deformed, there is no well tied to the seismic, and the interpretation was purely based on the one made for the AR09_80-MIG, and in the fact that the two seismic lines are parallel to each other. In this way the process was trying to make the horizons and faults the more correlated as possible, between the two seismic lines.

For this thesis the re-interpretation of the AR09_80-MIG was done by inserting the well tops from the Benfeito-1 well that was previously tied to the seismic and follow the more strong reflectors

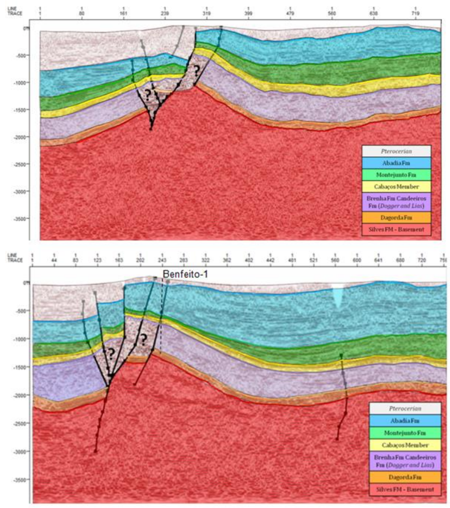

Figure 4 - AR05_80-MIG Interpreted Seismic Lines

Due to the geological interpretation, in both lines is present a flower structure which is a folded structure associated with strike-slip faults.

In areas where strike-slip faults occur in converging crust, or transpression, rocks are faulted upward in a positive flower structure. In areas of strike-slip faulting in diverging crust, or transtension, rocks drop down to form a negative flower structure. Flower structures can form hydrocarbon traps. The term "flower structure" reflects the resemblance of the structure to the petals of a flower in cross section.

It is difficult to follow the reflectors in both lines on the center of the faulted area, the seismic is very chaotic due to the movement of salt, and the reactivation of the Hercynian basement faults.

However the Grés the Silves Formation also considered Basement (red section of the lines), has not been confirmed by drilling, it's being assumed that the top of the Triassic is a strong reflector found at the what has been assumed has the base of the massive salt from the Dagorda Formation, because the Benfeito-1 well total depth is not corresponding to the top of the Dagorda Formation.

All the others formations are present as well tops for the Benfeito-1 Well, and were followed along the seismic line with the exception of the Candeiros Formation and Coimbra Formation (Dogger and Lias) include on the thickness from the Brenha Formation. The reflectors were very poor in terms of amplitude, so was impossible to follow and mark as a horizon with some accuracy.

For this thesis the interpretation was only based on the well tops from the Benfeito-1 and following the reflectors along the line to the southern part which is the most deformed, but this is not corresponding to the reality, has can be explained ahead.
This AR09_80-MIG seismic line, besides the Benfeito-1 well near the acquisition survey, there is other exploratory wells presented along the line from North to South, Aldeia Grande-2, Benfeito-1, Freixial-1, Arruda-1 and Montalegre-1.

For the MILUPOBAS report interpretation for this line, they take into account all the well tops from this wells but in terms of the faulted area they still had some difficulties in following the reflectors.

The horizons interpreted are six but the isopchas created are only five, because in the case of the last unit considered (Grés de Silves Formation- Basement) there's no velocity information of the Benfeito well logs, due to the total depth being in the middle of the formation above (Dagorda Formation).

The velocities used from the most recent unit to the oldest are:

Abadia Formation	– 3809 m/sec;
Montejunto Formation	– 5240 m/sec;
Cabaços Formation	– 6200 m/sec;
Brenha Formation	– 5961m/sec;
Dagorda Formation	– 4937m/sec;

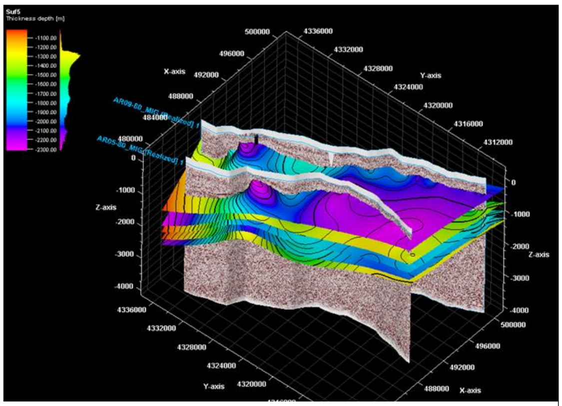

Figure 5 - Representation of all the isopachs computed at once.

We can infer that Abadia Formation thickness varies between 200m to 1100m, the Montejunto Formation between 300m to 1600m, Cabaços Formation between 500m to 1700m, Brenha Formation between 800m-2000m and finally Dagorda Formation 1100m to 2300m.

Geostatistical Seismic Inversion (GSI)

The objective of this chapter is to apply a Geostatistical Seismic Inversion (GSI) to the AR09_80-MIG 2D line using the hard-data from the Benfeito-1 Well, with and without zones

For both cases, with and without zones, the results of the (GSI) presented in this work were obtained from 32 Simulations with 6 iterations.

The main objective of a stochastic model algorithm for seismic inversion is to improve reservoir characterization, by producing high resolution numerical models that have two properties: their honor a physical relationship (convolution model) with the actual data, and the numerical model reflects the spatial continuity and the global distribution functions.

GSI:

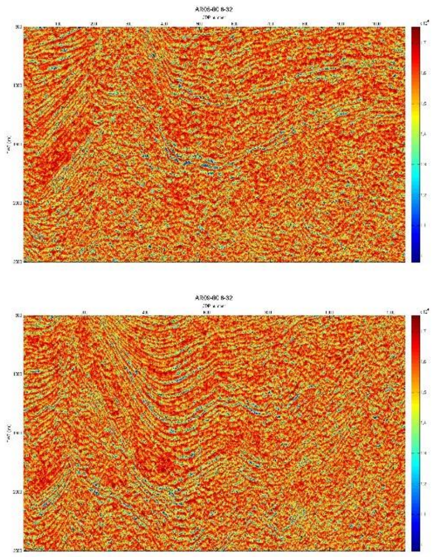

Figure 6 - AR05_80-MIG seismic lines 6-32 realization and AR09_80-MIG seismic lines 6-32 realization.

Generally speaking, the GSI for both seismic lines, AR05_80-MIG and AR09_80-MIG, are good and match with those expected for unexplored areas like this. At the end of the inversion procedure, the impedance model shows continuous layers that are in concordance with the main seismic reflections

In terms of correlation coefficient values for both seismic lines the best global correlation coefficient between real and synthetic seismic data is around 0.9, which is a very good value of correlation.

While the convergence of the inversion methodology is good, we may doubt about the distribution of the acoustic impedance values in the retrieved inverse model. There are preferable locations or particular impedance values.

GSI with zones:

First of all the seismic line AR09_80-MIG was cropped from the (800ms-2800ms) into a size with 1-245-501 cells, in this way where is the most interested part of the seismic line, and the nearest to the Benfeito-1 well.
And recurring to the software petrel a zonation based on the horizons interpreted was made, into 7 zones, figure7.

In terms of the hard data from the well Benfeito-1 to compute the acoustic impedance, for each zone, was used the RHOB-log and Velocity logs, the wavelet was a phase zero between 0-50.

The description of the zones on figure 23:
Zone 0 – Is the interval of the Upper Jurassic Sediments, which are from 0-135m of depth on the Benfeito-1 well report.

Zone 1 – Corresponding to the interval of the Abadia Formation, and to compute the value for AI, because the RHOB log only started at the 995meters of depth in the well, an equation was used to deduce the density from the velocity log.

This equation is Gardner's equation:

$$\rho = d \times {V_P}^{f}$$

This in an empirical equation to be used when the Vp is known but the density not. The d and f coefficients are chosen based on the lithology of the formation, in this case the one applied was for limestone and purposed by Gardner, which are 1.36 for d and 0.38 for f, see equation 6.

Zone 2 , Zone 3 & Zone 4 – Corresponding to Montejunto Formation, Cabaços Formation and Brenha (Aalenian-Pliensbachian) Formation respectively were computed used the normally the Velocity Log and RHOB log.

Zone 5 – Corresponds to the Dagorda Formation, in this case the Velocity log and RHOB logs end at the 3273m, which is not corresponding to the end of this formation, so the acoustic impedance was computed using the values that we have, extended to all the thickness formation.

Zone 6 – Corresponds to the Grés de Silves Formation, also considered the Basement on the interpretation, and for this there is no logging information, no RHOB or Velocity. So according to a gravimetric modeling paper, (Miranda et al.,2010) the average density for this formation is 2.9 g/cm3 and according to the MILUPOBAS report the velocity is around 5000 to 5500 m/s, so calculating AI knowing this and generate into random numbers between this values on excel, was the way to create AI for this formation.

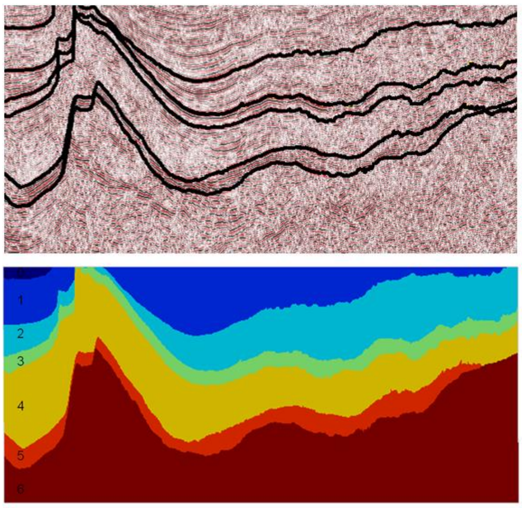

Figure 7 - The first image, is the real AR09_80-MIG Seismic Line and the horizons marked. The second image is the zones for each of the horizons marked.

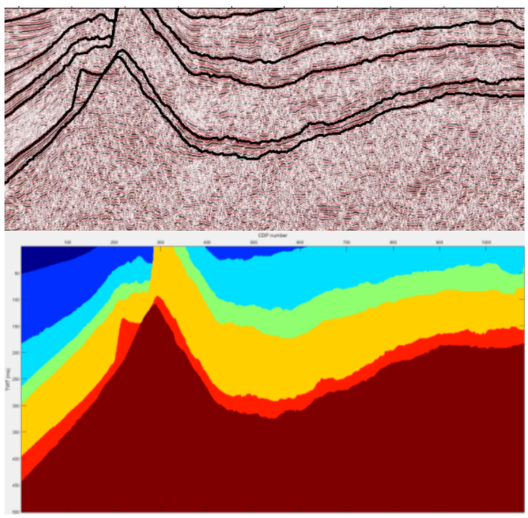

Figure 8 - The first image, is the real AR09_80-MIG Seismic Line and the horizons marked. The second image is the zones for each of the horizons marked.

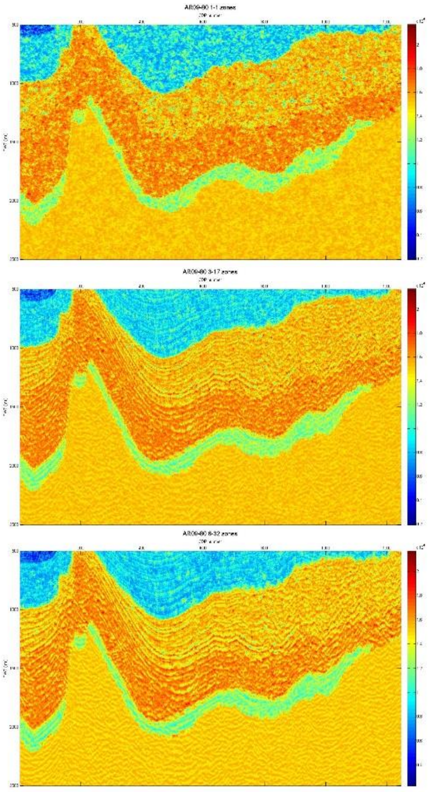

Figure 9 - Results obtained from the geostatistical seismic inversion for AR09_80-MIG, corresponding to 1-1; 3-17 and 6-32.

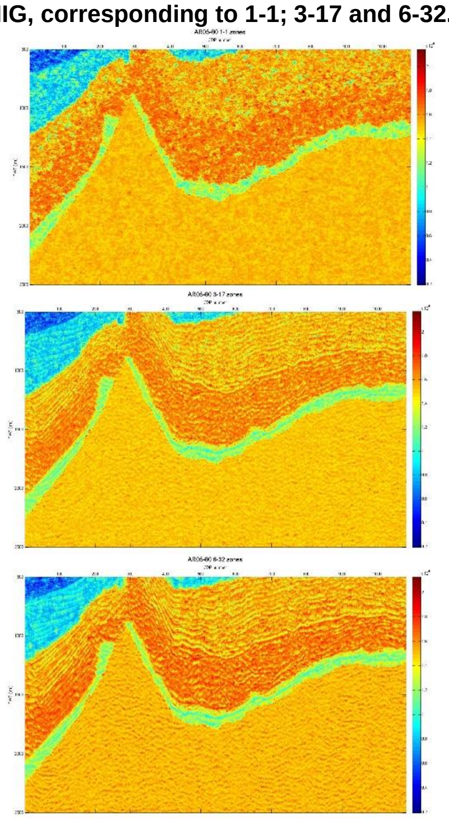

Figure 10 - Results obtained from the geostatistical seismic inversion for AR05_80-MIG, corresponding to 1-1; 3-17 and 6-32.

In both seismic lines, AR05_80-MIG and AR09_80-MIG the GSI the retrieved acoustic impedance models seem plausible and do agree with the observed seismic. As expected in the areas where the seismic do not present a good quality and a low signal to noise ratio, the spatial continuity is reduced, and the corresponding coefficient correlation are low at the end of the inversion procedure.
The center zones in both seismic lines (AR05_80 and AR9_80) are the ones that present a better convergence of the model and the best correlation values closest to 1, due to the presence of strong reflectors well replicated on the acoustic impedance GSI images.
In this areas the uncertainty of the model is high, is the case of the last zone (zone 6), the equivalent to Grés de Silves and Basement formation on both seismic lines, the seismic is highly chaotic and the values in terms of correlation still very low. Remember that the values used for the hard data in this zone were calculated regarding data from density and velocity of some authors, which bring even more uncertainty.
In terms of convergence of the application of the GSI, the results between the real seismic and the synthetic in both of the Seismic lines were good, and the main reflectors are well reproduced

Conclusions

This work was successfully done, in terms of the different types of information, available and studied for the Arruda Sub-basin, Portugal.

In terms of Geological Framework, the regional geology information was summarized, for the Lusitanian basin and for the geodynamics and tectonics of the Arruda Sub-basin.

For the well logging data, Petrophysical values were calculated successfully, for the different stratigraphic units on the Benfeito-1 well. The results obtain are not very encouraging in terms of hydrocarbon accumulations, but provide a better analysis of the lithology in each layer.

On the Seismic Interpretation chapter, the two 2D seismic lines, were re-interpreted

according to structural and stratigraphic analyses and with the known well tops, corresponding to Benfeito-1 well.
And last for the Geostatistical Seismic Inversion (GSI), with and without zones, the process was new, for this kind of under-explored areas. The results were encouraging in terms of the characterization of the sub-surface elastic properties, but more data needs to be added, to get better and more accurate results.

This study shows the importance of data integration particularly for unexplored sedimentary basins as the Arruda sub-basin. We integrated all the available information in terms of geology, petrophysics and geostatistical modeling to characterize the spatial distribution of the subsurface properties of interest, i.e. acoustic impedance.

For this part of the Arruda Sub-basin, with the analysis of the real data, we can infer that is a very promising area in terms of possible hydrocarbon accumulations, based not only on the petrophysical interpretation but also on the inverted models that show consistent low acoustic impedance values for layers at the same depth.

This work should now be improved with the integration of other nearby wells and seismic reflection lines improving in this way the petrophysical and seismic interpretations, which will allow more reliable acoustic impedance models.

The results presented here an added value for the knowledge of this sub-basin. At our knowledge this is the first time a subsurface elastic model is presented for this area. Also, this work presents a reliable solution for the application of geostatistical seismic inversion methodologies where only few well data is available.

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