Seismic facies analysis applied to P and S impedances from pre-stack inversion

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Summary

Seismic facies analysis is a very powerful tool for multi-attribute interpretation. The same approaches, developed for post-stack interpretation of seismic or impedance volumes, can be successfully applied in the pre-stack domain to interpret P and S impedance inverted cubes. Through a real case study and two different approaches, we show that S attributes provide valuable and non redundant information for the description of the reservoir.

Introduction

The recent generalization of AVO or elastic inversion methods provides geophysicists with efficient tools for reservoir characterization. However, how powerful they may be, these methods still require a detailed interpretation phase, and rise new difficulties that the interpreter has to tackle in order to determine the relevant parameters in the huge amount of available data. For instance, what is the amount of non-redundant information in the S attributes? Which reservoir properties are significantly related to P or S information ? Which parameterization, such as impedances, reflection coefficients, or Lame parameters, is likely to provide the best access to reservoir properties ? To answer some of these questions, we propose a general methodology for pre-stack multi-attribute interpretation, based on statistical pattern recognition, and involving supervised and unsupervised segmentation algorithms in a probabilistic frame.

Methodologies

In the following, two approaches for pre-stack multi-attribute interpretation are presented : a 2D and a 3D approach. Both consist in the prediction of reservoir quality, with supervised and unsupervised statistical pattern recognition algorithms, and both allow for a quality control and an assessment of uncertainties.

In the 2D approach (Déquirez et al., 1995), we proceed to a segmentation of the traces in the reservoir window, in order to produce a facies map of the reservoir, and its associated probability map. Each trace portion is characterized by a certain number of attributes, derived from the P and/or S impedance response at the reservoir level. The segmentation takes place in the attribute space, and two complementary workflows are possible. Firstly, the supervised analysis consists in the use of geological information, through training traces around well locations, for guiding the facies determination. The integration of the geological a priori is based on discriminant analysis. This approach allows a straightforward interpretation of the resulting seismic facies maps, but requires a sufficient number of wells to be carried out. Conversely, the unsupervised analysis does not involve any geological a priori, and is based on cluster analysis, carried out in the attribute space. However, well information is involved for the a posteriori interpretation of the seismic facies.

In the 3D approach (Fournier et al., 2000), the segmentation is not applied to portions of traces at the reservoir level, but directly to the seismic voxels within the reservoir window The same methods of supervised and unsupervised analyses can be applied for the voxel segmentation. However, in the following study, we have privileged the supervised approach, for interpreting the voxels in terms of dominant lithologies. We first determinate the seismic-scale dominant lithology at wells, and we associate it with P and S impedances, filtered in the seismic bandwidth, for the different voxels along the wells. The resulting training sample is then used for a discriminant analysis, to predict the dominant lithology at the seismic scale for the whole seismic volume of P and S impedances. Finally, a dominant lithofacies cube, and its associated probability cube, are available.

We propose to demonstrate the interest of the two approaches described above on a real case study of a deep-offshore turbiditic field, situated on the west-African continental margin. The data set is constituted of :

- Three wells W1, W2 and W3 (W3 being deviated) with density, P and S impedance and lithofacies logs.
- Two P and S impedance cubes, derived from pre-stack inversion of five high resolution PP seismic angle-cubes, according to the methodology developed by Tonellot et al. (2001).

2D approach

We started our study by a 2D analysis, aimed at investigating the contribution of the S attributes to the reservoir characterization. A 36 ms window (19 time samples), corresponding approximately to the uppermost depositional sequence of the reservoir, was extracted from the P and S impedance cubes. We first performed a supervised analysis, with a training sample constituted of 4 classes, corresponding to the 3 wells, plus an “hemipelagite” class, defined from a stratigraphic interpretation of the area. (Figure 1). Well W1 is representative of a reservoir dominated by coarse-grained sand turbidites ("good reservoir"). Well W2 corresponds to a reservoir where the sands are not so thick as for well W1 ("intermediate reservoir"). Finally, well W3 is representative of a geological environment, with fine-grained sands and mud turbidites (poor reservoir quality). The training sample is composed of seismic traces extracted in the vicinity of the 3 wells (121 traces for each well), plus those selected in the area of expected hemipelagic deposits.

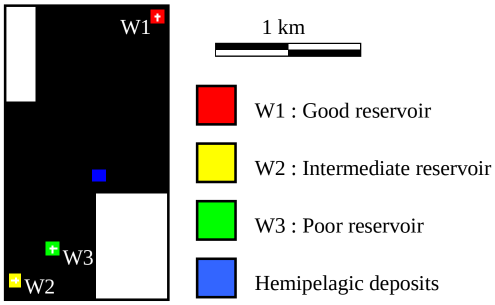

Figure 1: Training sample for the supervised analysis

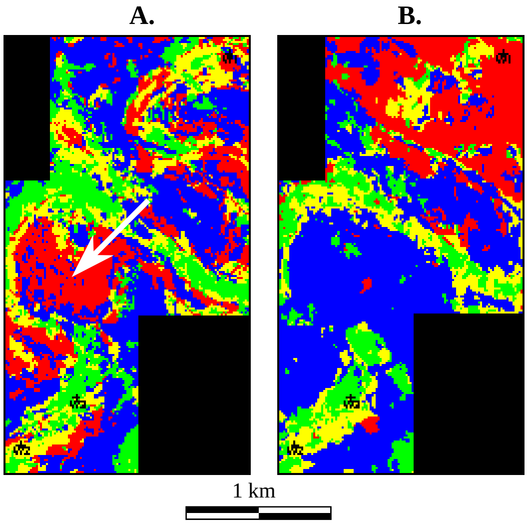

Figure 2: Supervised analysis, using A. attributes from P impedance alone, and B. attributes from P and S impedances.

Attributes were computed from the extracted time values of impedance within the reservoir, through principal component analysis (PCA). Two cases were analyzed. We first studied the P impedance only, and used 7 principal components, corresponding to 90 % of the total variance of the initial 19 impedance values within the reservoir. We then studied the combination of P and S impedances. The initial 38 P and S impedance values were brought down to 13 attributes, still corresponding to 90 % of the total variance. Note that the fact that twice the number of attributes was required, after PCA, to reach the same amount of variance, is a first proof of the non-redundancy of P and S attributes. The results after supervised analysis are shown below on Figure 2. A channel-shaped lineament clearly appears on both maps. However, on map A, the area designated by the white arrow is assigned to the "good reservoir" class. This observation does not fit with the geological knowledge about the nature of the turbiditic deposits. The probability map (not shown here) indeed shows that the assignment is associated with a very low probability in this zone. On map B., the same area is assigned to the hemipelagite class, with a much higher probability, and in agreement with the geological context. The overall quality of the discrimination is also much better on map B. Those remarks, as well as other results concerning the cross-validation of the training sample traces, clearly speak in favor of the use of the S attributes.

We then proceeded to an unsupervised analysis with P and S attributes. As can be seen on Figure 3, the resulting map shows a significantly different facies distribution from the one of Figure 2.B, which is not surprising, since the segmentation was guided by the data alone, and not by the interpreter's a priori decisions.

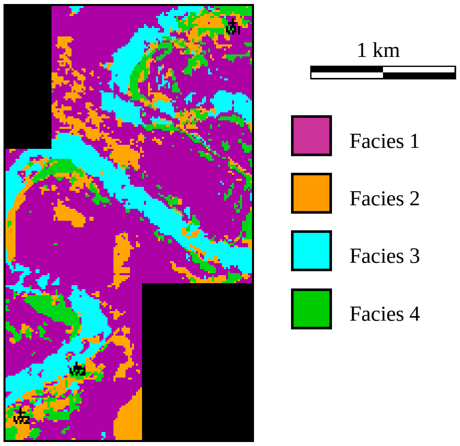

Figure 3: Unsupervised analysis on attributes from P and S impedances.

A very precise channel shape, corresponding to facies 3, can be observed. Facies 2 and 4 are located on the sides of this channel. The two wells with sand turbidites, W1 and W2, are located in areas where those two facies are proeminent, thus impliying that they could be representative of reservoir zones. W3 however, is located on the boundary of the channel. Looking back at Figure 2, this explains why this feature is not as well identified in the supervised approach, the training sample mixing two different geological environments in a single facies. Facies 1 of Figure 3, and the hemipelagite facies of Figure 2 approximately occupy the same area, which therefore probably corresponds to the deep offshore shale deposits. This exemple shows the complementarity of the supervised and unsupervised analyses, which both tend toward the same interpretation of a channel with reservoir zones on its edges.

The maps presented above were obtained with principal components computed from the impedances filtered in the seismic bandwidth (i.e. low-cut filtered, to remove the very low frequencies). Tests with other parameterizations were also carried out. The reflection coefficients led to poor results, and identified zones of very low spatial continuity. The full inverted impedances did better, and showed slightly different results from those obtained with the filtered impedances, due to impact of the very low frequency component introduced through the a priori model used in the inversion process (see Tonellot et al., 2001).

3D approach

After upscaling the lithologies at the wells in the whole reservoir window (approximately 180 ms), consistently with the seismic bandwidth, we used the wells W1 and W2 to build a training sample, to calibrate a discriminant function allowing the propagation to the seismic volume of the lithologies at well. Four dominant lithofacies were identified. Lithofacies hemipelagite 1 (blue) and 2 (purple) correspond to the standard argileous deep offshore deposits, hemipelagite 2 being slightly denser and found deeper than hemipelagite 1. The two other lithofacies correspond to the turbiditic sedimentation, and can be either a reservoir facies, in the case of sandy deposits (yellow), or not (muddy deposits, green). The distribution of these facies in a IP-IS cross-plot is shown on Figure 4.

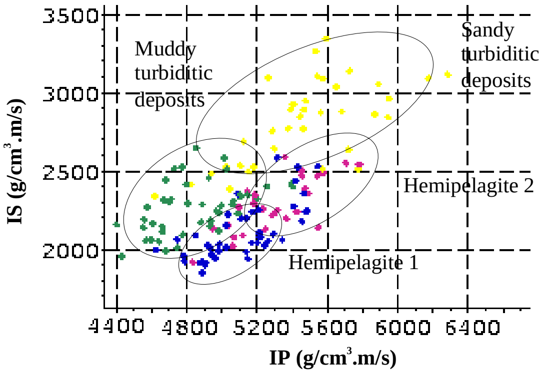

Figure 4: IP-IS cross-plot of the lithologies at wells 1 and 2, after upscaling

To evaluate the reliability of the discriminant function, we performed cross-validation tests. The principle of these tests is the following : each point of the training sample is reassigned to one of the classes, using a discriminant function computed with every other point but this one. If the attributes used allow a good discrimination of the training sample points, a majority of points should be reassigned to their actual class. Several tests were performed, with different types of attributes. The results obtained with P impedance alone are compared to those obtained with P and S impedances on Figure 5 below.

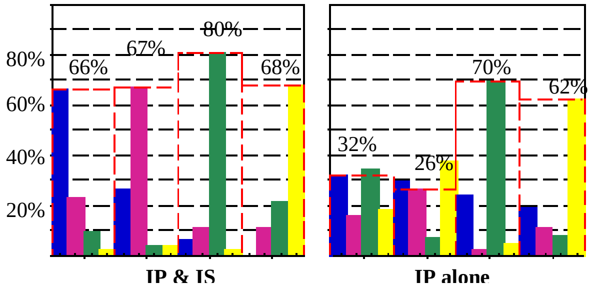

Figure 5: Cross-validation results of discriminant analysis, using IP & IS impedances, and IP impedance alone

As in the 2D approach, the interest of the S impedance is obvious. With P impedance alone, only 32% and 26% of hemipelagite 1 and 2 respectively are reassigned correctly. 20% of hemipelagite 1, and 40 % of hemipelagite 2, are misclassified in the sand facies, therefore rising severe doubts about the ability of the P impedance to identify reservoir zones. However, the use of P and S impedances allows a correct discrimination of 66% at least of every facies, and even 80% in the case of muddy turbiditic deposits. Moreover, almost none of the three non-reservoir facies are misclassified to the sand facies. In consequence, it seems that P and S impedances, used together, allow the identification of the sand facies, and hence, of the reservoir zone.

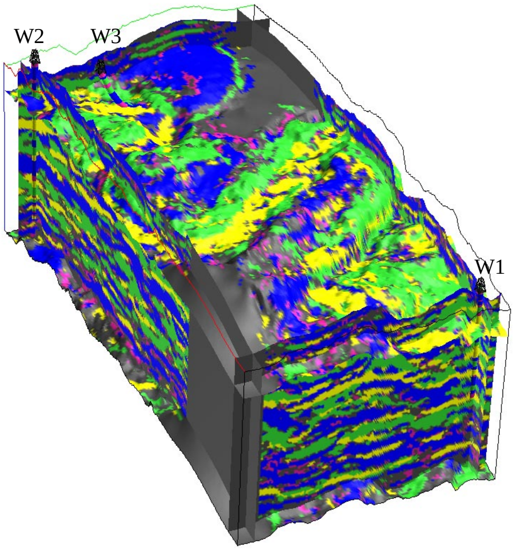

Figure 6: Dominant lithology volume, predicted from the joint use of IP & IS impedances

The “IP & IS” discriminant function was then applied to IP and IS inverted cubes to predict a dominant lithology for each voxel of the seismic volume, as shown on Figure 6. The top of Figure 6 shows a slice in the lithology volume, parallel to the top reservoir horizon, and located near the base of the 2D approach window. A channel shape is clearly visible, and appears to be filled with sand. Muddy turbiditic deposits occupy the sides of this channel, and the hemipelagic 1 and 2 facies are located far from the meanders, in agreement with the geological context. The sides of the cube show a very good match with W1 and W2 upscaled lithologies, and demonstrate the interest of the 3D approach, which allows to identify the sand beds in the whole reservoir window.

2D approach versus 3D approach

To compare the results from 2D and 3D approaches, we computed, in the 2D 36 ms window , the proportion of each facies of the 3D lithology cube. The results are presented on Figure 7 for the hemipelagite 1 and sand facies.

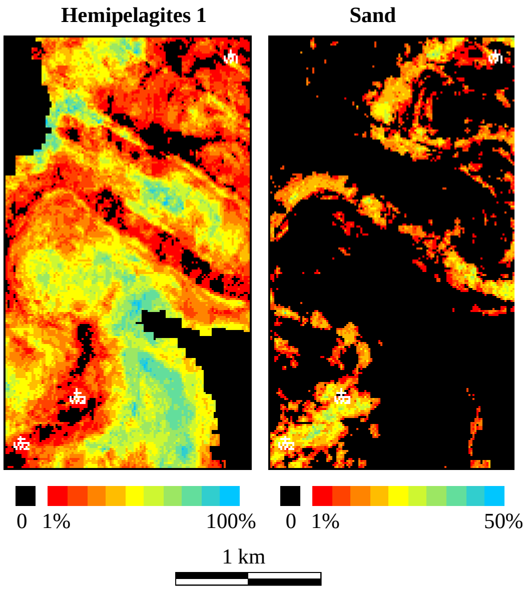

Figure 7 : 3D facies proportion in the 2D approach window.

The same channel shape, identified in the 2D approach on Figure 2 and Figure 3, is clearly visible on both maps of Figure 7, thus highlighting the convergence between the two approaches. The hemipelagite proportion map allows the identification of the deposits related to the turbiditic event, which are the thickest in the red and black areas, and are thin or absent in the green and blue areas. The sand facies proportion map allows the delineation of the reservoir zones. Sand can mostly be found in the channel and on its sides, around the wells. The fact that sand is present in the channel may seem in contradiction with the results of the 2D supervised approach (Figure 2), since part of it was attributed to the “poor reservoir” facies. A closer comparison shows that most of the area assigned to the “poor reservoir” facies corresponds to areas of low sand proportions, the rest of the channel being assigned to the “intermediate reservoir” facies. The only divergence between the 2D and 3D approaches is found in the north east corner of the map, almost entirely assigned to the “good reservoir” facies on Figure 2.B, while no or few sands are found in this area on Figure 7. However, the unsupervised map on Figure 3 closely looks alike the sand proportion map on Figure 7. The supervised results of Figure 2.B might be different because of differences in the S impedance response in the training sample area associated to the “good reservoir” facies. The unsupervised map indeed shows a complex distribution of the facies 1, 2 and 4 in this zone. Globally, the 2D and 3D approaches show a remarkable convergence.

Conclusion

The use of the S impedance in the seismic facies analysis provides valuable information for the identification of the reservoir zones, either in the 2D or in the 3D approaches. The combination of P and S impedances significantly increases the lithologic discrimination power of the seismic data, thus showing the interest of the joint inversion methodology, developed by Tonellot and al. (2001), in the context of reservoir geophysics. The seismic facies interpretation methodology presented in this paper offers a wide range of multi-attribute interpretation tools, allowing a neutral view of the data with the unsupervised analysis, as also a geologically oriented view with the supervised analysis. It allows for the determination of the most relevant attributes, and provides a constant assessment of the uncertainties attached to the interpretation of the seismic data in terms of reservoir quality.

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