# Evaporitic Section Characterization Using Inversion and Bayesian Classification

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## Abstract

After first oil field discovery in the pre-salt province in Santos Basin, more than 200 wells were drilled accessing the pre-Aptian section containing carbonates reservoirs. Those reservoirs are situated below an evaporitic section presenting variations in terms of thickness from few meters up to more than 2000m.

The evaporitic section is strongly complex in geological terms, impacting many areas of reservoir characterization and exploitation such as: velocity models used on seismic migration and conversion from time to depth, horizontal and vertical positioning, uncertainties analysis, illumination studies, geomechanical issues, operational safety, etc.

Aiming to better predict the salts behaviors, studies of seismic inversion and probabilistic facies modeling have been developed to this entire section.

In this paper we will illustrate few results obtained studying a specific data-set from an existing (real) pre-salt field in Santos Basin.


## Introduction

The evaporitic section in Santos Basin has complex geological structures such as diapirs, mini basins, folds, allochthonous salt etc. The formation process of those structures may be related to halokinetic forces as well as extensional and/or compressive efforts. Beyond that, this sedimentary salt bedding has great mineralogical variability:

- Halite, that is the dominant component of salt rocks, representing around 90% (Yamamoto *et al.*, 2016) of the evaporitic section, with average density of 2.2 g/cm³ and seismic interval velocity around 4500 m/s;

- Anhydrite and Gypsum having both high values of density and interval velocity (compared to Halite); facies with low solubility. The basal Anhydrite represents the main seal of reservoirs in this referred basin;

- Tachydrite, Carnallite, Sylvite etc, whose densities and velocities are lower than the previous described groups. They are also more soluble, a factor making well's drilling difficult in this basin.

The salt complexity is identifiable on seismic data. On the study region it was possible to distinguish three patterns of seismic facies (figure 01):

- Stratified seismic facies: it is the portion of seismic where the contrast of impedances occurs, with a monotonous sequence;

- Homogeneous seismic facies: regions where there are no reflections on seismic. This facies may be associated to the existence of thick layers of halite or sub-seismic layers of other salt minerals;

- Chaotic seismic facies: it consists of intensely perturbed reflections that are disordered, heavily folded and discontinuous. However, it is possible to visualize internal contrast of acoustic impedances.

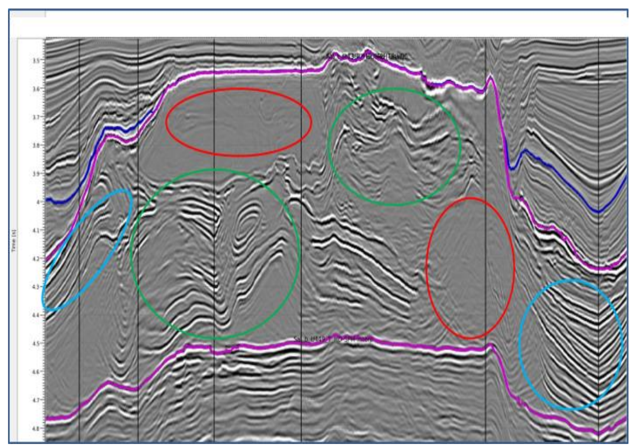


**Figure 01**: *Arbitrary seismic section. Red ellipses show homogeneous seismic facies, blue and green lines circulate stratified and chaotic patterns, respectively. Purple lines are top and base of the studied salt section*.

Those descriptions regarding the observed salt percentage and domain of patterns of seismic facies are in accordance with the review presented by Jackson *et al.* (2015).

The homogeneous and chaotic facies are associated to the great salt walls (figures 01 and 02). In the mini-basins it predominates the stratified pattern. With the development of the studies on the evaporitic section, it was noticed that many reflections in seismic were produced by side lobes reflected on interfaces with strong contrasts of impedance (Maul *et al.*, 2016).

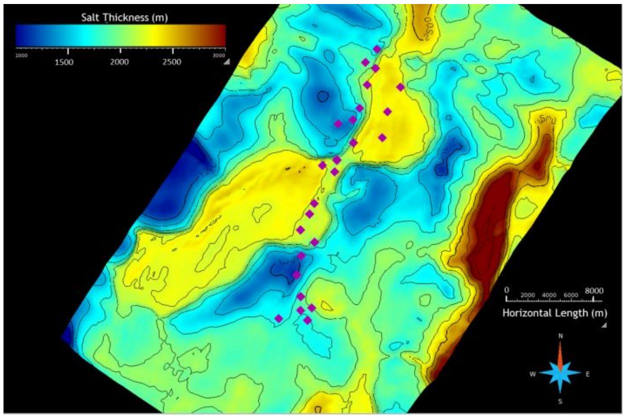



**Figure 02**: *Salt thickness map. The salt domes are represented by layers more than 2000 meters thick (yellow and red areas) while the mini basins in blue are less than 1500 meters thick. The purple points represents the location of the wells.*

### Method and Results

Several authors (Maul *et al.*, 2015, Jardim *et al.*, 2015, Maul *et al.*, 2016, González *et al.*, 2016 , Gobatto *et al.*, 2016 and Yamamoto *et al.*, 2016) suggest the seismic attribute characterization of evaporitic section. In this work we performed this characterization based on the following data-set: logs of 25 wells, seismic in time and depth domains, velocity model and interpreted horizons. The work was performed on three stages that are intrinsically linked:

- Well analysis

- Seismic inversion

- Probabilistic facies modelling

The drilled wells crossed through many different geological contexts. Part of the wells had measurements of compressional sonic, density, resistivity and gamma-rays logs inside the salt layer. However, in order to ensure a feasible statistical treatment, it is mandatory to complete the information for the entire section.

The methodology purposed by Amaral *et al.* (2015) suggests use the drill cutting samples to complete the needed information for the entire evaporitic section. Silva & Rodrigues (2016) suggested re-interpreting well-site lithology interpretation supported by other logs.

Taking the entire information regarding logs and/or cutting samples for the evaporitic section it is possible to group the “salts” in three categories:

- Background Velocity (Halite)

- High Velocity Salts (Anhydrite and Gypsum)

- Low Velocity Salts (Tachydrite, Carnallite, Sylvite)

Figure 03 presents the described categories proportion in each well location.

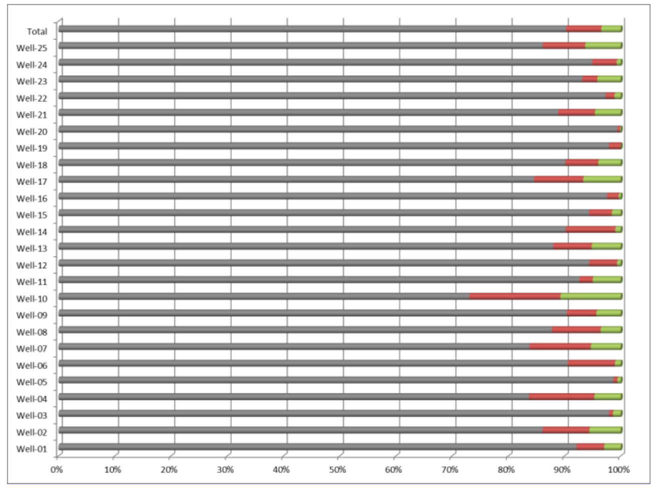



**Figure 03**: *Graphic with proportions of grouped salt for each well. Grey means Halite, Red refers to High Velocity Salts and Green to Low Velocity Salts.*

The salt proportion varies on each well and its magnitude is related to the geological conditions where the well was drilled. On the great walls Halite rocks represent more than 90% of salt occurrence. On the mini-basins the proportion of salt with high and low velocity varies between 10% and 20% (only one well has more than 30% of non-Halite occurrence).

The well logs have sample rate and frequency higher than the existing in seismic data. To guarantee the relation between the information during the inversion and the facies classification it was necessary to resample the data on *λ/4* (one quarter of the wavelength), to get close to the spatial average of the seismic wave. The resampled facies log increases the Halite proportion, because thin layers of different minerals are under the seismic resolution and cannot be imaged by any amplitude data (figure 04).

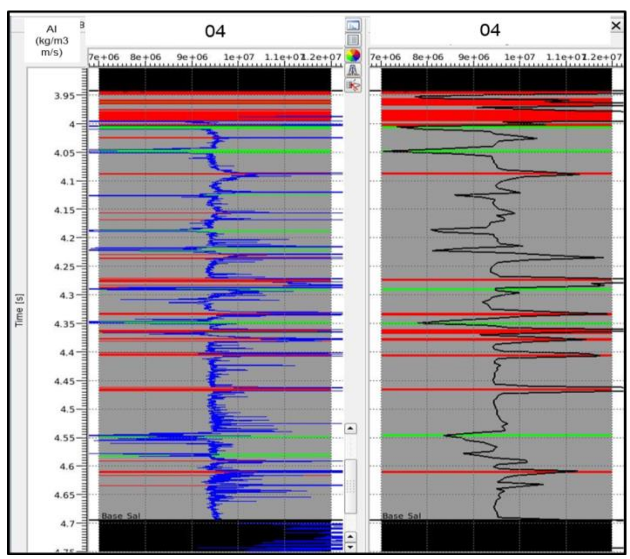



**Figure 04**: *Upscale applied to well 04. Acoustic impedance calculated with well logs and grouped facies are shown on the right. The impedance with* Backus *average filter and the facies resampled to 4ms are shown on the left.*

Seismic is the main method to interpret the spatial distribution of rocks for the interested zones, however it has some limitations that can strongly affect the studies:

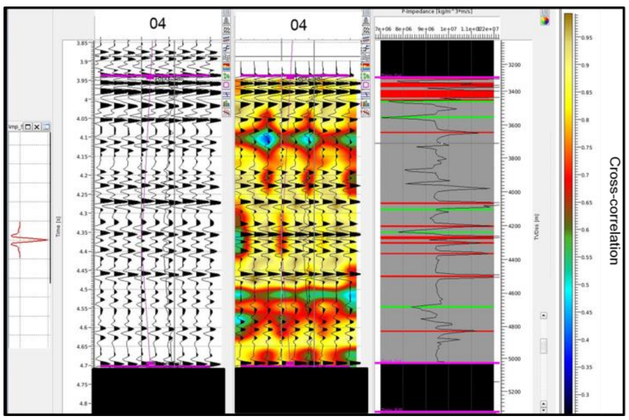
-It carries information of contrast of impedance between rocks;

-The frequency content is limited around 5 to 30 Hz;

-Reduce vertical resolution with depth.

To mitigate these effects, seismic inversion is an alternative; however the process of impedances calculation is an inverse problem with multiple solutions. Besides that, the inversion of seismic data is complicated by several reasons: 1) the noise contaminating the data, 2) the simplifications of modelling to reduce the process time consuming and 3) the uncertainties related to well-tie procedure, time to depth conversions and wavelets estimation.

In figure 05 we try to exemplify the difficulties when performing well-ties.




**igure 05**: *Seismic-tie of well 04. From left to right. 1) Wavelet estimation 2) 9 traces around the well 3) 9 synthetic traces calculated with impedance information of the well, where the hot colors represent higher correlation between seismic and synthetic traces 4) Facies-log of grouped salts with the well's impedance filtered with Backus average.*

The algorithm used here was the sparse spike inversion. This method estimates the reflection coefficients that reproduces the seismic trace with minimum number of spikes.

Fifteen vertical wells, drilled on different salt contexts, were tied to seismic. At the well locations where the homogeneous and stratified seismic facies predominates, the correlation coefficients between seismic and synthetic traces were high (above 0.8). At the regions where chaotic facies is the dominant pattern the correlation coefficient was lower, with values around 0.6.

The wavelet used (Figure 06) on the inversion was calculated from the wavelets average estimated at each well location.

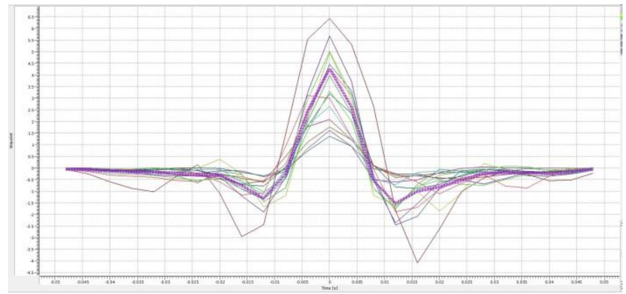


**Figure 06**: *Wavelets estimated for 15 wells used on the inversion process. The averaged wavelet is the purple highlighted one.*

The low frequency model was built through the interpolation of impedance values (log-calculation) obtained for each well following the stratigraphy determined by the horizons (model-based inversion).

The low frequency model together with the wavelet and seismic was used in the acoustic inversion resulting on a volume of acoustic impedance (AI). The time window used in the inversion began 150ms above the evaporitic section and finished other 150ms below it. The values of AI for Halite are around 9.3 X $10^6$ kg/m³ m/s. Figure 07 presents the inversion results taking amplitude seismic as background (out of evaporitic section).

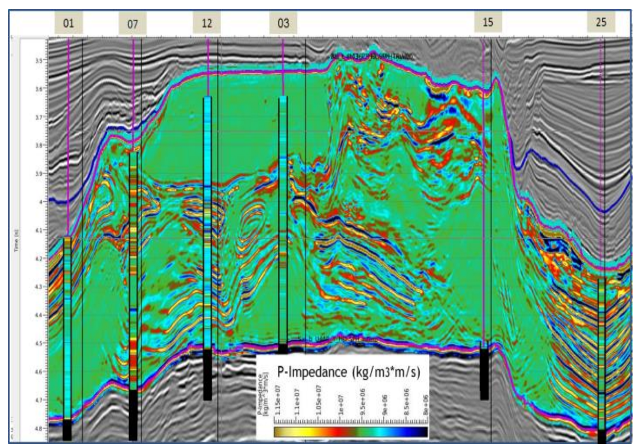



**Figure 07**: *Arbitrary section showing the impedance values of inversion, together with the AI from the wells and the seismic as background. Green portions represent Halite occurrences; Blue portion represent Low Velocity Salts and Yellow to Red indicates High Velocity Salts.*

The inversion data and lithological logs were used as input to facies probabilistic classification, based on *Bayes Theory*, as it was suggested by Meneguim *et al.*, (2015). This theorem describes the probability of a hypothesis to be true if a certain event happens. In this work we want to estimate the probability of occurrence of salt from our *prior* knowledge acquired with well data and seismic.

$$P(Ai|X) = \frac{P(X|Ai)\,P(Ai)}{P(X)}$$

- X is the value of the attribute volume and, in our case, it is the acoustic impedance.

- Ai represents the salt grouped facies, described on logs.

- P(Ai) and P(X) are the *prior* probabilities.

- P(Ai|X) and P(X|Ai) are the *posterior* probabilities of Ai conditional to X and X conditional to Ai.

The *Bayesian* classification constructs rock properties prediction probabilistic scenarios (Avseth, 2010). The knowledge of *prio*r information is important in *Bayesian* theory because the posterior probabilities are strongly influenced by *prior* probabilities. Therefore, errors on the interpretation of *prior* probabilities will be amplified in the *posterior* models.

Probability Density Functions (PDF) were estimated for the facies (Halite, Low Velocity Salts and High Velocity Salts) using the curves upscaled of well's data (figure 08). The PDF is an equation used to describe a continuous probability distribution.

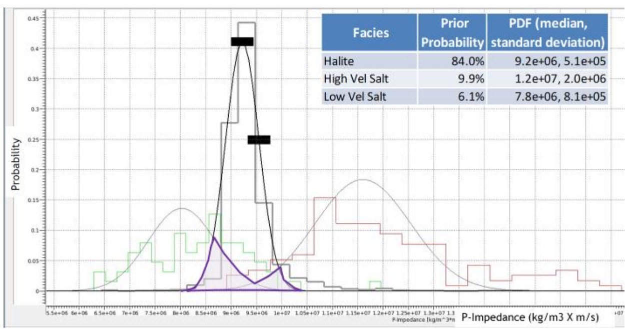



**Figure 08**: *Probability Density Functions (PDF) for each salt. Table with values of the prior probability, median and standard deviation.*

Testing the width of density functions on the histogram, it is noticed that large windows produces a smooth model with low resolution, reducing the intercalations of facies compared to well data. If the bins are thin, the variability of the PDF will be too high compared to the seismic resolution. Hence it will not be possible to apply the PDF to the AI cube.

The purple zone exposed in the figures 08 and 09 represents the overlap area on the PDFs. The risk of misclassification is relatively high on these areas, but using the ***Bayes's*** rule a probability will be estimated for each facies generating scenarios which mitigate the uncertainty associated with salt characterization.

The occurrence of Halite (in wells) is around 90%, and it was our initial guess for the *prior* probability, however after several tests this value was reduced to 84%. This decrease was due the high proportion of halite presents in the model comparing with observed in wells and seismic data. Another reason to reduce the *prior* probability is that the number of wells drilled in the mini basins (where there are more stratifications and non-Halite salts) is smaller than the salt domes.

After all analysis and applying the *Bayes Theorem*, each sample of AI cube from the inversion will be related to a probabilistic value of occurrence of the petrofacies, generating statistical scenarios for each salt (figure 09).

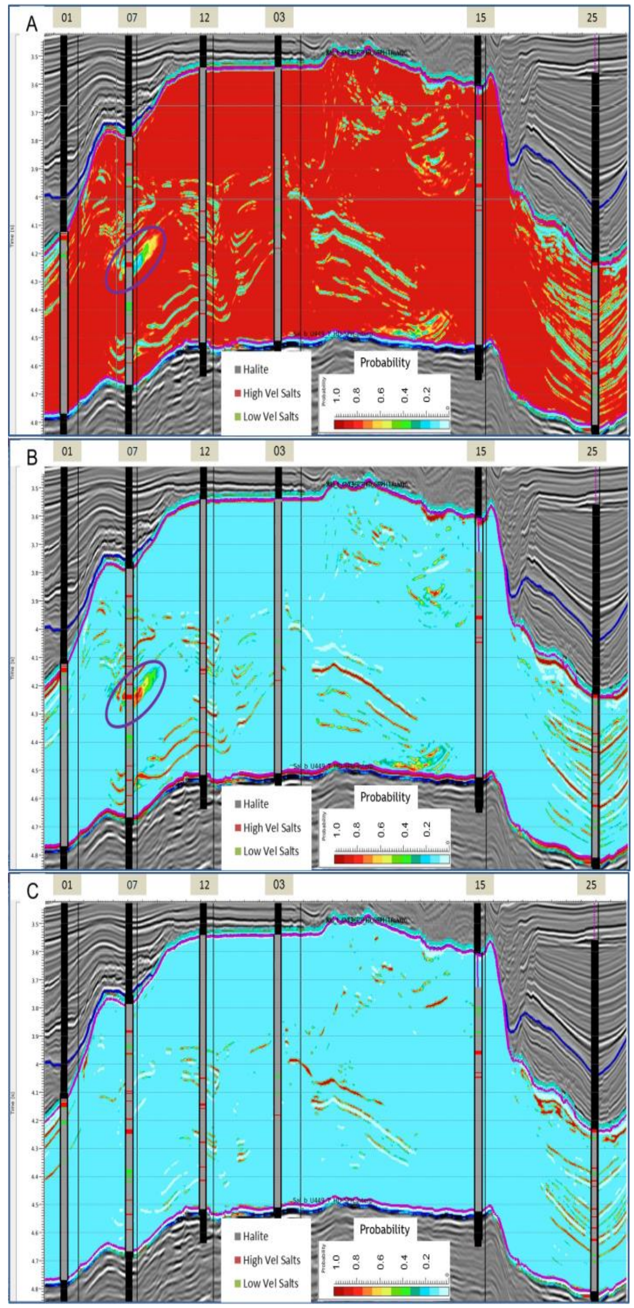



**Figure 09**: *Probabilistic scenarios for each salt together with the petrofacies logs of some wells A) Halite probability B) High Velocity Salts C) Low Velocity Salts*

As a final result, we have a most probable facies volume, constructed by comparing the probability for each petrofacies and scenarios at a given data point and assigning the facies type of the most probable facies to that data point (figure 10)

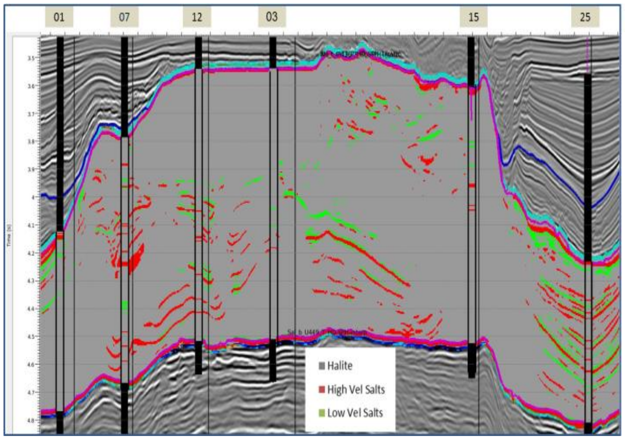



**Figure 10**: *The most probable petrofacies model together with the grouped salts of some wells (Halite, High Velocity Salts and Low Velocity Salts)*

## Conclusions

The evaporitic section in the studied area has high geological complexity, observed in both wells and seismic data. Considering the huge amount of available information, the results of this work are robust to characterize the salt. However, it is necessary to have in mind the limitation of resolution of seismic method, around 20 to 30m in this case.

Analyzing the studied wells, it was verified that 90% of the salts content is Halite, 6% represents the High Velocity and Density Salts and the remaining fraction represents the Low Velocity and Density Salts (4%). In the areas with salt domes, Halite is 90% of the structure, while in min-basins the proportion falls to around 80% or less, indicating a correlation between “salt-thickness” and “salt-variation”. This was mentioned by Oliveira *et al.* (2015).

The seismic inversion enables to satisfactorily recover rocks´ acoustic properties. The result of inversion is robust, with values of impedance extracted from cube similar to the wells calculations (Figure 10). However, at some regions, where the chaotic facies were presented, the correlation between logs and seismic traces were low (something between 0.5 to 0.6)

The *Bayesian* facies classification method brings additional value to application of inversion results when associated to rock properties information from wells. Instead of deterministic relations obtained directly from facies, the probabilistic facies cubes allow to evaluate the non-uniqueness relation between impedance and seismic facies.

This facies model is robust as it was checked by blind tests where the model was predictive about the possible kinds of salt found in the wells not included when performing the studies (figure 11).

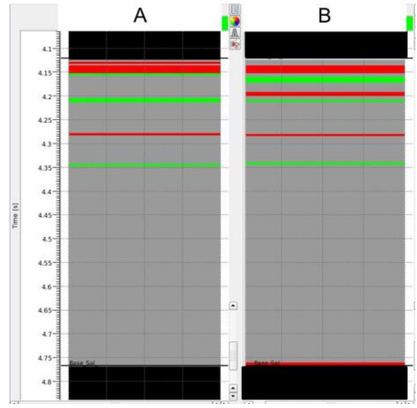



**Figure 11**: *Comparison between the facies of the well 23 (A) and the trace extracted from the model (B)*

It is worth to remind that the model calculates the bigger probability of facies occurrence in a specific region based on the *prior* knowledge of drilled wells and seismic. Areas with poor knowledge (few wells drilled) are not recommended to do this kind of approach.

The characterization of facies in evaporitic section has become an important input to other disciplines:

1) on the forecast table of geological environment for well drilling planning because the soluble salts are a great obstacle to stability of the well walls;

2) geomechanical models of the reservoir;

Another important subject to be discussed is about the regions without seismic reflections so that the model cannot evaluate them. Possible reasons for this absence of reflections are the layer thickness of the salt below the resolution of seismic and/or illumination problems due to acquisition parameters.

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