Characterizing Evaporitic Section and Geomechanical Properties Using Seismic Inversion, a Case Study for Santos Basin

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Abstract

Knowledge of the evaporitic section above pre-salt reservoirs in Santos Basin is an important aspect to be observed when preforming geomechanical analysis, especially regarding drilling aspects, injection and production rates.

Existing geomechanical models do not necessarily represent a realistic geology for this section concerning the salt variety observed when drilling wells. Occasionally, geologic features are indicated when preparing the well forecast only by taking into account the seismic description and uncertainties identified for the well path.

Therefore, a more realistic description of rock properties in the evaporitic section can be used to improve the studies on drilling safety and geomechanical models. One way to achieve this is by using model-based seismic inversion and well log derived relations between acoustic impedance and properties used as input to the geomechanical models. Additionally, statistical facies classification, based on Bayes´ Theorem, can be carried on the evaporitic section with the same intent.

In this study we present the seismic inversion results along with the workflow used to generate other rock properties for a specific area in Santos Basin proposed by Maul *et al.* (2016).

Introduction

The Pre-Salt Reservoirs in Santos Basin are currently the most important area of interest for the oil industry in Brasil. The salt section occurring above these reservoirs imposes several challenges regarding geomechanical studies. When analyzing seismic amplitude response and well log data within the salt section, it is possible to note that stratifications are not geologically represented in conventional interpretations.

Therefore, incorporation of new features in the standard procedure for building models for this section is necessary to obtain a more feasible cap. By doing so, it is possible to create geomechanical models including a more robust geological approach, considering specific characteristics, such as the stratified layers and their rock properties inside the salt section.

For this reason, Maul *et al.* (2016) presented a recursive workflow (Figure 1) to generate a more realistic model, including existing stratification within the salt section. Through this workflow, the model is improved and each result becomes a new input for the next stage.

The first results using this workflow or, more precisely, to faculty its developments, are vastly registered in technical literature (Amaral *et al.* (2015), Borges *et al.* (2015), Jardim *et al.* (2015), Maul *et al.* (2015), Meneguim *et al.* (2015), Oliveira *et al.* (2015), Borges (2016), Gobatto *et al.* (2016), González *et al.* (2016), Meneguim *et al.* (2016) and Yamamoto *et al.* (2016)).

The position of stratifications is better refined at each step of the cycle, trying to represent the lithological heterogeneity, which influence the seismic response within the referred evaporitic section.

The methodology presented in this work uses information from seismic inversion to correctly position the different salt stratifications inside the evaporitic section and improve the resolution of this stratification due to the deconvolution process during the inversion. Afterwards, it is possible to perform facies classification and to generate rock properties for geomechanical analysis and studies, as described in Teixeira *et al.* (2017).

Method

The methodology proposed by Maul *et al.* (2016), presented in González *et al.* (2016) and Gobatto *et al.* (2016), suggests a recursive approach for velocity, inversion, facies and uncertainty models building (Figure 1).

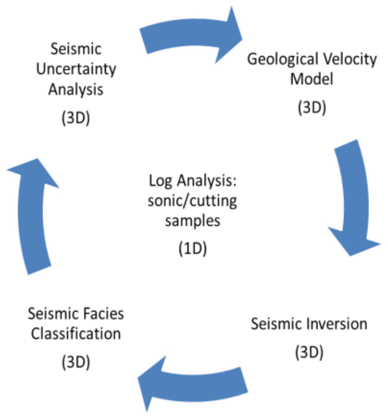

***Figure 1**: Workflow used to generate a more realistic property model (adpated from Maul* et al.*, 2016 in Gobatto* et al.*, 2016 and González* et al.*, 2016).*

There are same papers mentioning many different types of evaporitic rocks within salt section of Santos Basin, such as halite, anhydrite, gypsum, carnallite, tachyhydrite, sylvinite. Furthermore, the occurrence of other types of rocks, such as igneous, siliciclastic and carbonate rocks is also described (Amaral *et al*. (2015), Jackson *et al.* (2015), Oliveira *et al.* (2015) and Yamamoto *et al*. (2016)).

After the first approaches of the methodology presented concerning aspects related to seismic velocity results and usage, Meneguim *et al.* (2015) have shown how to use a probabilistic approach of seismic facies analysis on the acoustic impedance data to generate salt heterogeneity within the evaporitic section. This process is known as Bayesian facies classification. By using Bayes´ Theorem, geophysical and geological information are combined to build probability volumes of facies occurrence. Figure 2 shows the resulting facies distribution.

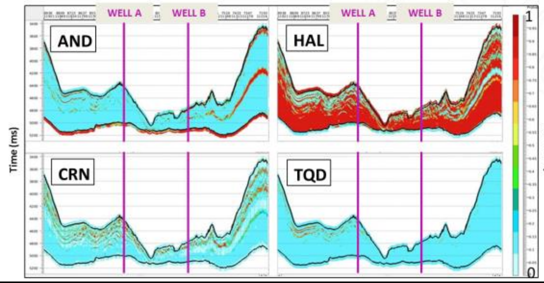

Figure 2*: Arbitrary section showing probability of facies occurrence, for each class of evaporite. Red indicates the most probable occurrence. AND, HAL, CRN and TQD stand for anhydrite, halite, carnallite and tachyhydrite, respectively (Meneguim* et al.*, 2015).*

The previously mentioned papers emphasize the need to separate the evaporitic rocks in three groups, following the separation designed by Amaral *et al*., (2015) and Yamamoto *et al*., (2016). These groups could be established as: Low Velocity Facies - LVS (carnallite, tachyhydrite, sylvinite); Halite-facies (background) and High Velocity Facies - HVS (anhydrite, gypsum). For all other studies, the separation based on seismic velocities appears to be enough, except for geomechanical analysis. In these cases, it appears that seismic inversion is mandatory, especially in areas where it is observed other kinds of rocks.

Regarding facies analysis and classification, following the results presented in Meneguim *et al.* (2015), Meneguim *et al.* (2016), Yamamoto *et al.* (2016) and Teixeira *et al*. (2017), seismic inversion results must be one of the main inputs to be considered, as it helps to minimize ambiguity in amplitude response, bring well control and layering acoustic properties.

In this paper, we use the first inversion result as an input for a second round of inversion in order to mask a few non geological phenomena observed when performing the inversion model. We also suggest using pseudo-well to locally control acoustic impedance well log extrapolation for low frequency model in the inversion process (Teixeira & Queiroz, 2016).

After performing seismic inversion, it is important to empirically model the behavior of density logs cross plotted against P-impedance also calculated using well information, in order to generate a function to derive a 3D density model as described through the following (Figure 3).

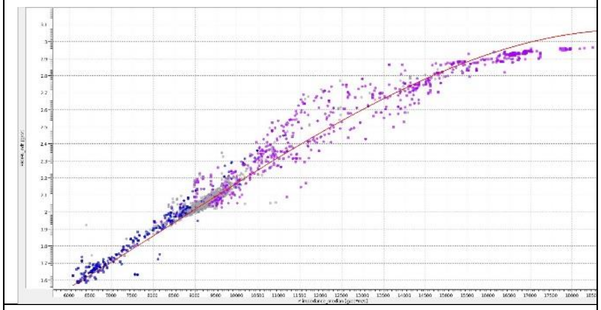

Figure 3*: Cross-correlation between density logs and P-Impedance, calculated using only well information (complete logs). The blue, gray and purple dots represent low-density salts, halite and high-density salts, respectively. The red curve is a 3rd degree polynomial fit to all the data.*

The same approach (well log correlation) was used to obtain others rock properties for geomechanical and geophysical studies, such as Young Modulus and P-Velocity.

Examples and Applications

We started with a 3D seismic full stack volume and well logs in the area of interest in the Pre-Salt region of Santos Basin. The process of seismic model-based inversion in two steps consisted in gridding the evaporitic section proportionally to the seismic mapped base and top of the salt horizons. Then, the P-impedance log information was used to build the initial low frequency model, which was merged to the seismic data to generate a P-impedance 3D volume in seismic inversion process. The gridding based only in the base and top of salt horizons does not respect the halocinesys responsible for the complex domic geometry and the different types of rock intercalations present in the salt section and evident in the seismic amplitude volume. Thus, the resulting volume of P-impedance shows patterns inconsistent with the geology represented by the seismic data (Figure 4).

A second round of inversion is then carried out. For this round, the initial model considered is the result of the first step, masked for halite constant values of P-impedance, based on well statistics. The merge frequency in this step is higher than in the first one, since the initial model already incorporates some seismic information. The resulting P-impedance volume is now more coherent with the geology since seismic information was incorporated, especially concerning the presence of halite domes, as it can be illustrated in Figure 4, in comparison with the result of the first round of inversion.

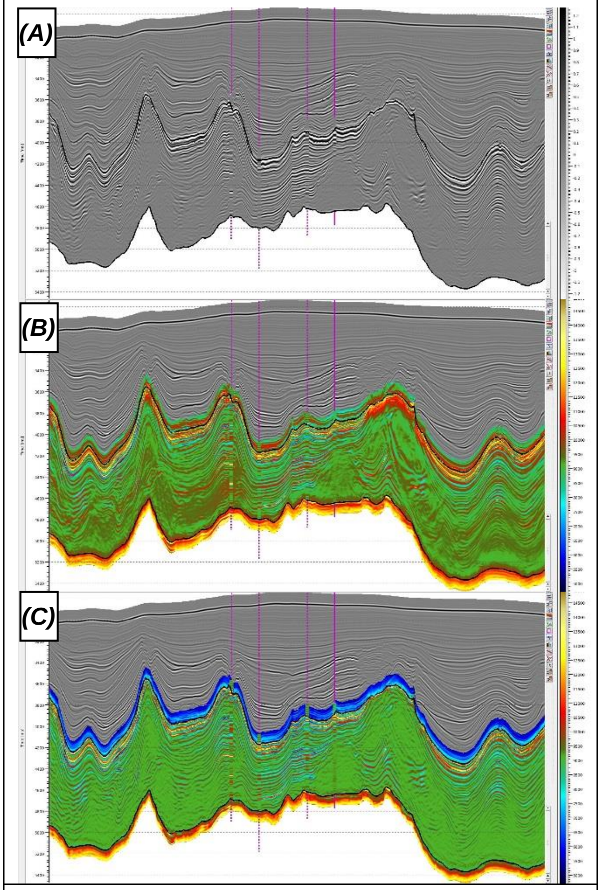

***Figure 4**: **(A)** Seismic arbitrary section in the region of interest; **(B)** P-impedance section resulting of the first step of inversion; **(C)** P-impedance section resulting of the second step of inversion. The non-geological features are not present anymore.*

Additionally, it might be needed special attention to some in wells with no lateral seismic continuity. The inversion process tends to extrapolate these events and incorporate them in the P-impedance volume output through the initial model in a way that is not in agreement with geologic features observed by seismic data, nor it is possible to mitigate only by the two steps procedure described above.

In this case, we successfully include in the workflow the use of pseudo-wells as a control mechanism in the inversion process. The identified events with no lateral continuity are ceased by the inclusion of control pseudo-wells log in agreement with seismic information in the initial model. The results and comparison of this procedure can be observed in Figure 5.

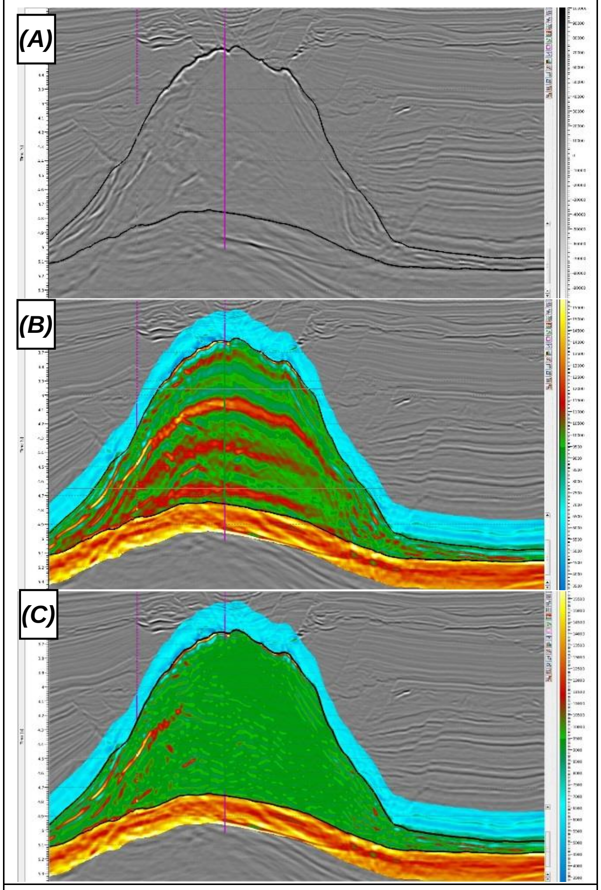

***Figure 5**: **(A)** Seismic section showing a strong event in well with no lateral continuity; **(B)** P-impedance section from inversion with no use of control pseudo-wells. The event is extrapolated to the domic reflection free region observed on the seismic section; **(C)** P-impedance section from inversion using control pseudo-well. The event is not extrapolated to the domic reflection free region anymore and its extent is controlled.*

Once the P-impedance volume is obtained, well log are used to empirically model geomechanical parameters, following the recipe described in the previously section. In the case presented here, 3rd degree polynomial fits were obtained from P-velocity, density and Young Modulus as functions of P-impedance (Figure 3). These polynomial relations were then applied to P-impedance volume, obtaining volumes for the geomechanical parameters that can be observed in Figure 6.

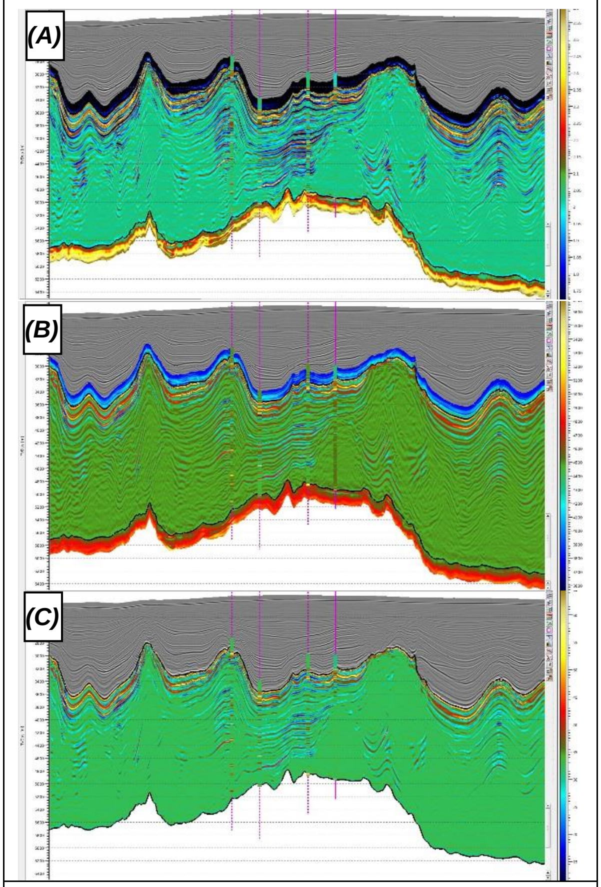

***Figure 6**: Empirically modelled geomechanical parameters from hard well data. **(A)** Density; **(B)** P-velocity; **(C)** Young modulus.*

Finally, salt separation by density values (from well data) were used to obtain the Bayesian facies classification. The evaporitic section lithology was divided in three facies: High Density Salt Facies, Halite Facies (background) and Low Density Salt Facies. The probability density function for each facies were determined by using statistics from wells. The resulting volumes presented in Figure 7 are probability of occurrence of each facies. Additionally, a volume of most probable facies is generated.

Conclusions

As previously discussed, studying the Pre-Salt Reservoirs in Santos Basin is a complex task. This difficulty is not only due to the reservoir lithology, but also occurs because of the important layer above the reservoir, an evaporitic section containing all the complexity described in this paper.

The concerns related to evaporitic section increases in importance when performing geomechanical studies, once real geologic aspects have to be considered in planning well drilling.

The model-based inversion followed by seismic facies classification seems to be the best approach when trying to obtain reasonable evaporitic section information regarding reliable spatial position as well as reasonable geomechanical properties values.

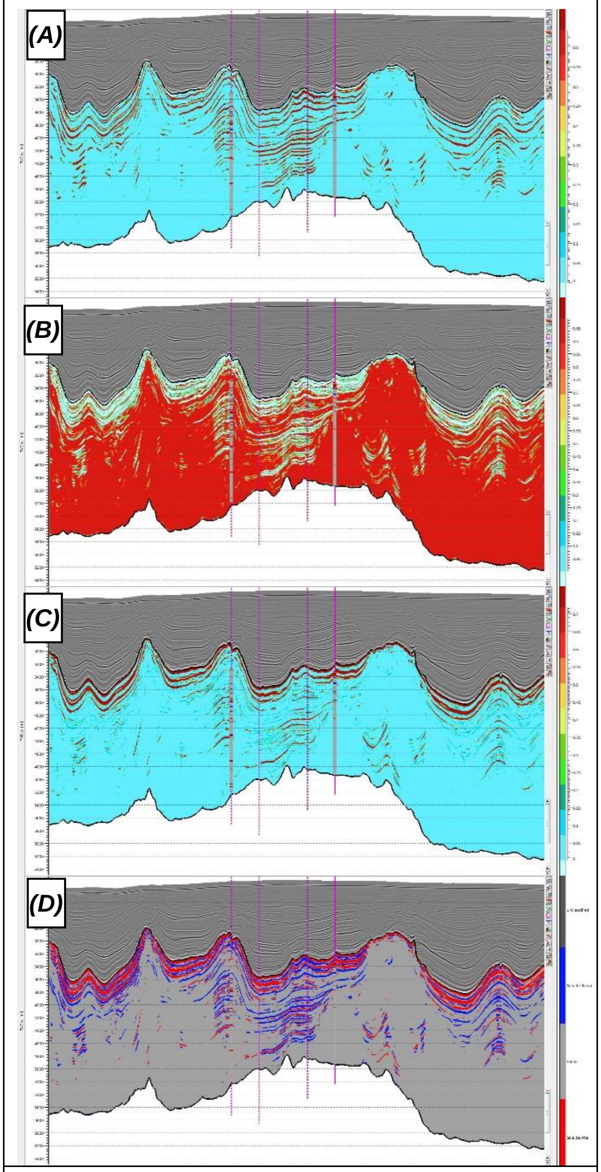

***Figure 7**: Bayesian facies classification for the case study. Red indicates higher probability. **(A)** Probability of occurrence of Low Density Salt Facies; **(B)** Probability of occurrence of Halite Facies; **(C)** Probability of occurrence of High Density Salt Facies; **(D)** Most probable facies.*

As mentioned here, there are several ways to deal with the evaporitic section regarding real stratification positioning as well as values of geomechanical properties assigned to each identified stratum. We explored the main aspects involved in seismic inversion within the salt section and the importance of seismic facies classification for geomechanical modelling Therefore, we believe seismic model-based inversion, combined with seismic facies classification and properties modelling using well logs, is a way forward in solving questions related to resolution, seismic classification, rock properties and its uncertainties.

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