Salt-Focused Inversion in the Santos Basin

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Abstract

The evaporitic section that acts as seal for the pre-salt section reservoirs in the Santos Basin, Brazil, has a very significant thickness and includes several different salt layers with substantial velocity contrasts.

Therefore, a more realistic description of the evaporitic section's internal velocities, taking into account the different salt layers, can reduce problems during seismic processing, and can be an important input to build a velocity model for time-depth conversion, for further seismic reprocessing or for a more realistic geomechanical model.

This study is a follow-up on the work by Amaral *et al.* (2015), applying the methodology in development since 2014 and described in Maul *et al*. (2016) that models in detail the salt layers from both seismic and well-based information, and to understand how those layers change the interval velocity.

In this paper, we will explore a new proposal for building a more realistic and geologically consistent velocity model and show some applications for several geoscience disciplines such as illumination studies, seismic processing, inversion studies, facies classifications, depth uncertainties, geomechanics, reservoir uncertainties, taking advantage from the application of this approach.

Introduction

The Pre-Salt reservoirs in Santos Basin, offshore Brazil are currently the most important area of interest for the oil industry in Brazil. The reservoirs are situated in water columns in most cases bigger than 2000m, and located under more than 3000m of rocks, including the Albian Carbonates and a Salt Section varying from few meters to more than 3000m in the salt domes/diapirs.

Through the past few years, especially since 2014, we have been facing a great improvement in velocity modeling for many purposes in oil industry regarding geophysics such as: seismic illumination studies, seismic reprocessing, seismic amplitudes quality response and positioning, geomechanical analysis, well construction, etc.

Besides seismic processing evolution such as the increase in computational power, migration algorithms evolution, anisotropy concepts and so on, the velocity model seems to be a key aspect to observe in order to obtain better seismic reservoir images, allowing for more confidence in terms of seismic interpretation.

The methodology proposed in this work aims to use information from seismic inversion to correctly position the different salt stratifications inside the evaporitic section. Furthermore, allowing to assign more reliable interval velocities to those stratifications, giving more geology content in the velocity model, as required when performing depth migration. The same model could be used as a background to start a model-based seismic inversion.

Regarding the 3D analyses it is possible to mention the works performed by Maul *et al*. (2015), Oliveira *et al*. (2015), Borges *et al*. (2015), Jardim *et al*. (2015), Meneguim *et al*. (2015), González *et al*. (2016), Borges (2016), Meneguim *et al*. (2016), Gobatto *et al*. (2016) and Yamamoto *et al.* (2016) to build this kind of geological velocity model.

All the 3D analysis are supported by well statistical 1D analysis as described in Amaral *et al*. (2015) and Yamamoto *et al*. (2016).

Method

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

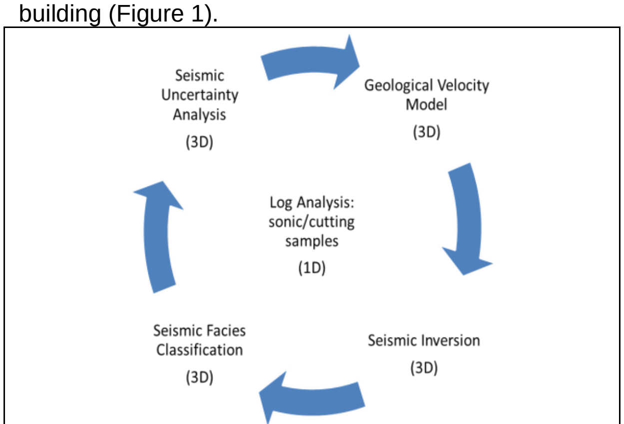

***Figure 1**: Proposed workflow to generate a more realistic seismic velocity model (adpated from Maul* et al.*, 2016 in González* et al.*, 2016 and Gobatto* et al.*, 2016).*

There are different types of evaporitic rocks inside the Salt section of Santos Basin such as halite, anhydrite, gypsum, carnalite, tachydrite, sylvite.

In order to obtain a more reliable velocity model for the Salt Section the mentioned authors suggest combining well information such as logs and cutting samples with any seismic response to update an initial velocity model.

This updated velocity model gives the background information for a model-based inversion. The seismic inversion results is one of the main inputs for the facies analyses and classification. Finally, adding uncertainties through a "Bayesian Classification", it is possible to generate new and more realistic velocity models for seismic processing and depth position purposes.

Meneguim *et al.* (2015) have shown how to use a probabilistic approach using seismic facies analysis to generate a heterogeneous salt section. Figure 2 shows the resulting facies distribution.

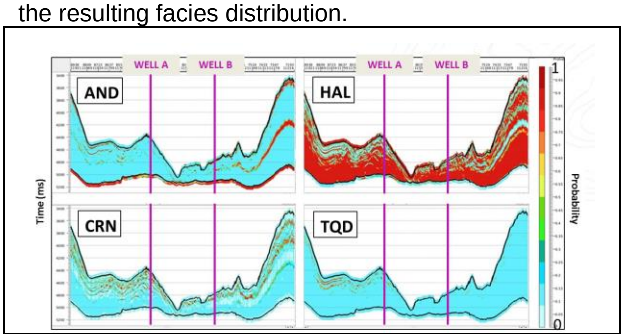

***Figure 2**: Arbitrary section showing the most probable facies, for each class of evaporate. Red indicates the most probable occurrence. AND means anhydrite, HAL is halite, CRN represents carnallite and TQD corresponds to tachydrite (Meneguim* et al.*, 2015).*

Several other disciplines such as illumination study, quantitative analysis for reservoir characterization, geomechanical studies, etc. can be enhanced by using this geological model considering velocity, acoustic impedance and/or seismic facies as input.

The purpose of this work is to point the main differences between conventional seismic reservoir inversion and salt section inversion. The first aspect to analyze is the existing well information regarding logs for the study area.

As the input for inversion, compressional sonic and density logs are needed. When only one of those logs exists, we need to use cross-correlation between them to generate the other log. In most of the cases within the salt section, we do not have the density log even when we have the sonic. In order to have density values where it has not been acquired, we use a cross-plot between P-sonic and density.

It is important to mention that we preserve the behavior between sonic and density using acquired information, i.e. where both logs were acquired. In this project, a 3rd degree polynomial fit was obtained from this cross-plot (Figure 3).

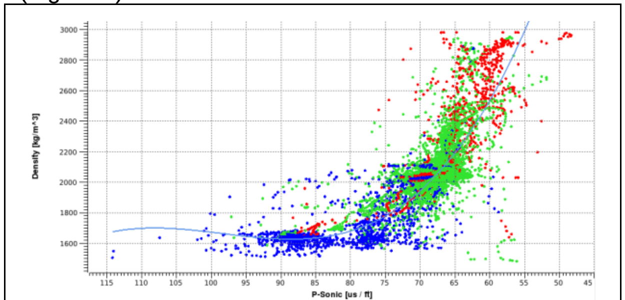

***Figure 3**: Cross-correlation between density and P-Sonic logs, calculated on the wells where we have complete logs. The blue, green and red dots represent low-velocity salts, halite and high-velocity salts, respectively. The blue curve is a 3rd degree polynomial fit to all the data.*

However, the majority of the wells have no logs within the salt section. The main reasons for the lack of needed information (logs) are the change of drilling phases and economy.

To overcome that, we use the interpreted lithologies (Amaral *et al*., 2015 and Yamamoto *et al*., 2016) and generate pseudo-logs using known correlations. The first step is to interpret the lithology of the whole evaporitic section in each well. We group the interpreted salt types in three pseudo-facies: low-velocity salts (carnalite, tachydrite, sylvite) or "LVS", halite, and high-velocity salts (anhydrite, gypsium), or "HVS".

Calculation of average interval velocity values for each salt in the Santos Basin can be seen in Meneguim *et al.* (2015). Amaral *et al*. (2015), besides calculating for their area, also mentioned several other authors and their respective tables for those velocities. Those velocities are converted to slowness values and applied to the regions where the sonic log wasn't acquired.

All the described procedures will carry the values we computed for the sonic to the density values, so we will have regions where both logs will be blocked to discrete values. This is clearly not as accurate as having actual logs run, but it is as much information as we could extract from the wells; and it will help for the entire seismic inversion procedure. Figure 4 summarizes all of the described steps explained above.

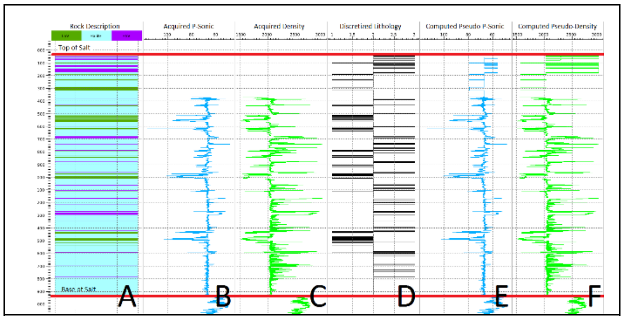

***Figure 4**: **(A)** Rock descriptions. **(B)** Sonic log as acquired for a given well, with missing information in a part of the evaporitic section. **(C)** Density log as acquired, also with information missing. **(D)** Discrete pseudo-facies log, discriminating between "LVS", halite and "HVS", obtained from rock interpretation inside the salt section based on "A". **(E)** Entire sonic/pseudo-sonic log, generated by completing the missing part of the acquired log in "B" with sonic values for each class as seen in "D". **(F)** Entire density/pseudo-density log, created by completing the missing part of the log in "C" applying the correlation from figure 3 to the sonic/pseudo-sonic log from "E".*

Another part of the process where the salt-focused inversion differs from general reservoir-focused inversion is the seismic-well tie, due to very thick sections and the lack of acquired logs for the whole section as mentioned above.

The first aspect is that the evaporitic section in most cases is a very thick section, in many regions with over 3km of thickness. This imposes additional difficulties in performing the well ties, bringing for instance questions about frequency (wavelet extraction).

Another point is that we usually do not have acquired well logs for the top few hundred meters of the salt section (due to the drilling phase shift). It is important to remember that we generated pseudo-logs for the entire salt section; therefore the synthetic seismogram to be tied will not be accurate for the top of the section. Consequently, we match the seismic "top of salt" horizon to the depth where the evaporitic section starts in the well. A similar problem is also observed in the base of the salt.

Since the impedance contrast between the overburden and the salt is always much higher than any other contrasts, this is a reasonable assumption to be followed.

Examples and Applications

The main examples we present are results from the three aspects we mentioned before in this paper.

In figure 5 we can see how the seismic amplitude stratification matches the lithology changes identified in the wells, and the distribution of salts in different wells. The salt layer is composed mainly of halite, with smaller percentages of anhydrite, carnalite, tachydrite, sylvite and other salts.

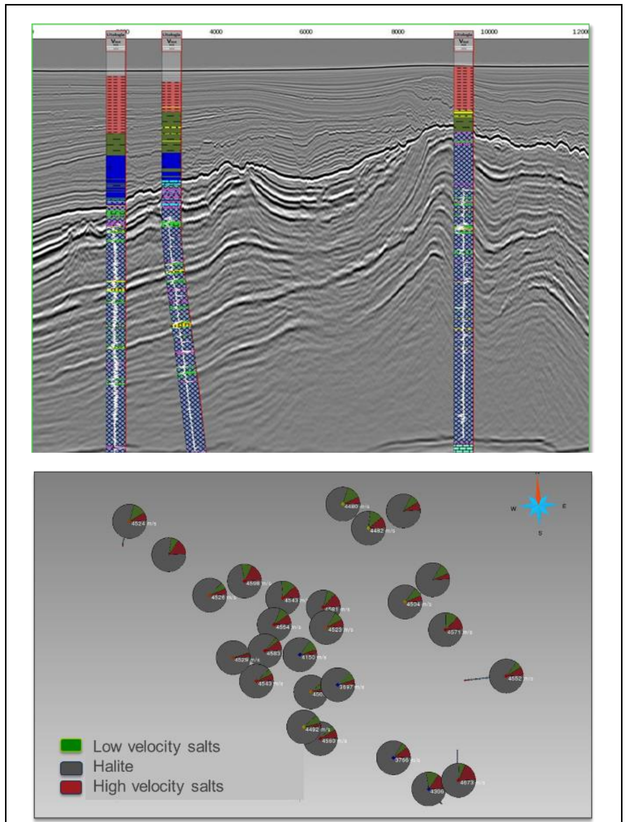

***Figure 5**: **(A)** Well lithology seen over the seismic amplitude data, showing the correspondence between seismic and the stratification seen on wells; **(B)** Distribution of different salt types in the evaporitic section for each well in a single study area. Blue is the halite percentage; green is the percentage of "low-velocity" salts (carnalite, tachydrite, sylvite); and red the percentage of "high-velocity" salt (anhydrite, gypsum). Adapted from Amaral* et al. *(2015).*

Figure 6 shows how much information we can add to the velocity model from an acoustic seismic inversion. The P impedance is used to distinguish between the different salt types, which in turn are used to replace the P-wave interval velocity from the original model to more realistic values in terms of velocity.

Araújo *et al.* (2016) *in* González *et al.* (2016) have shown that using the information from the stratification as input for a FWI (full waveform inversion) velocity model update and a RTM (reverse time migration), it is possible to generate a better processed image, as we can see in figure 7.

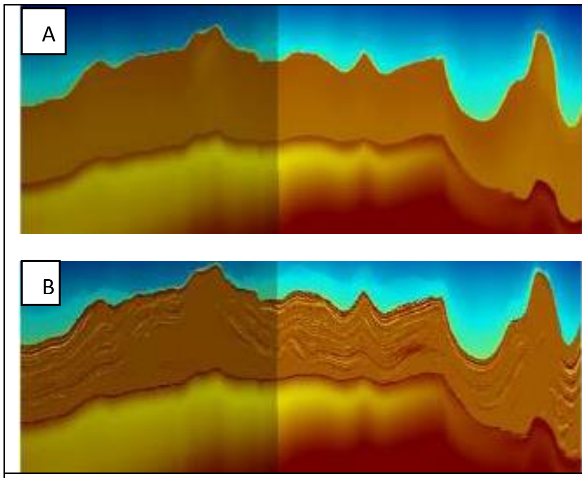

***Figure 6**: **(A)** Original salt velocity model showing no stratifications; **(B)** Velocity model obtained from the acoustic impedance. Adapted from Teixeira* et al. *(2016).*

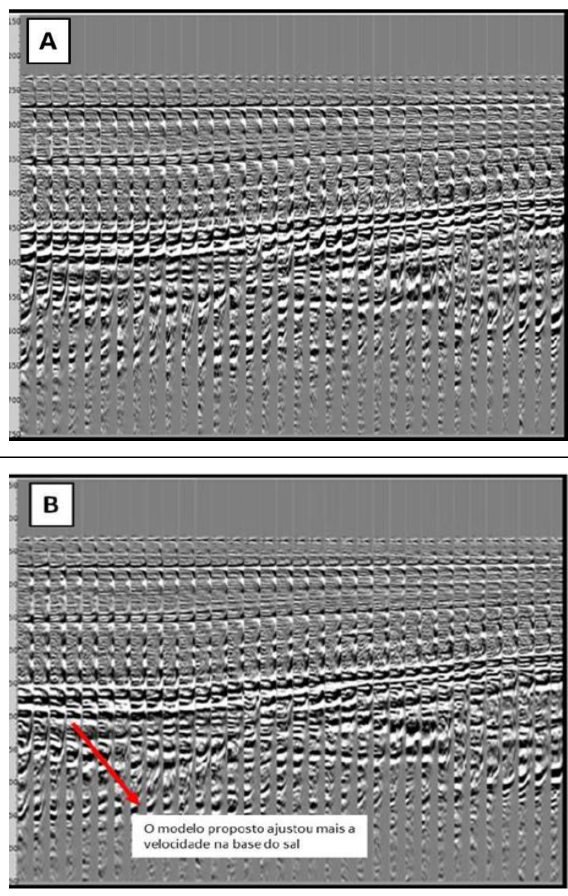

***Figure 7**: Migrated section obtained by FWI and RTM, using **(A)** constant velocity in the salt as input, and **(B)** stratified velocity in the salt as input. Notice the better flattening of the horizons, in particular the base of salt. Adapted from* Araújo et al. (2016) in *González* et al.*, (2016).*

Conclusions

As discussed previously, studying the Pre-Salt Reservoirs in Santos Basin is a complex task, due not only to the type of reservoir rocks, but also to the heterogeneity of the overlying rocks and structural aspects, and the reliability of seismic images generated with those concerns.

As presented here, there are several ways to deal with these problems and we explored the main aspects to be considered when applying seismic inversion to the salt section. Despite all these problems, we believe inversion is the way forward in solving questions regarding resolution, rock classification, uncertainties, and so on. Hence, this becomes a new research area to explore.

There are several applications for these models, in areas such as seismic processing, seismic illumination studies, model-based inversion studies, facies analyses and/or classifications, depth uncertainties, geological restoration and geomechanics. All the previous mentioned studies have shown more consistent results. These enable a better understanding of seismic responses and better reservoir characterization.

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References

Amaral, P.J., Maul, A., Falcão, L., González, M. & González, G., 2015. Estudo Estatístico da Velocidade dos Sais na Camada Evaporítica na Bacia de Santos. (14th International Congress of the Brazilian Geophysical Society 2015) – Rio de Janeiro – RJ, Brazil.

Araújo, S., Falcão, L., Oliveira, L., Rosseto, J., Maul, A., Gobatto, F. & González, M., 2016. Melhoria da Imagem no Pré-Sal, a partir de Atualizações de Velocidade de Alta Resolução no Pós-Sal e da Incorporação de Estratificações Dentro da Seção Evaporítica. (XV SIMGEF – Simpósio de Geofísica de Petrobras – Petrobras Internal Publication). Rio de Janeiro – RJ, Brazil.

Borges, F., Apoluceno, D., Selbach, H., Maul, A. & Lima, G., 2015. Thickness-Based Approach for Evaporites Seismic Velocities in Campos Basin. (14th International Congress of the Brazilian Geophysical Society 2015) – Rio de Janeiro – RJ, Brazil.

Borges, F., 2016. Combining Seismic and Well Data to Achieve Better Depth Prediction: a Case Study in Campos Basin, Brazil. 57th. SPWLA (The Society of Petrophysicists and Well-Log Analysts Annual Symposium). Reykjavik, Iceland.

Cunha, R., Maul, A., Noronha, M., Campos, J., Yamamoto, T., González, M., 2017. Importance of Interpreting the Rock Types inside the Evaporitic Section of the Santos Basin and Its Benefits (In preparation)

Gobatto, F., Maul, A., Falcão, L., Teixeira, L., Boechat, J.B., González, M. & González, G., 2016. Refining Velocity Model within the Salt Section in Santos Basin: an Innovative Workflow to include the Existing Stratification and its Considerations. (SEG – Society of Exploration Geophysicist – 2016) – Dallas – TX, USA.

González, M., Gobatto, F., Maul, A., Falcão, L., González, G., Oliveira, L., Meneguim, T. & Amaral, P.J., 2016. Proposed Workflow to Incorporate Stratification within Salt Section using Velocity and Seismic Attributes – (Third EAGE/SBGf Workshop on Quantitative Seismic Interpretation of Lacustrine Carbonates). Rio de Janeiro – RJ, Brazil.

Jardim, F., Maul, A., Falcão, L., & González, G., 2015. Estimating Amplitude Uncertainties through Illumination Studies for a Pre-Salt Reservoir. (14th International Congress of the Brazilian Geophysical Society 2015) – Rio de Janeiro – RJ, Brazil.

Maul, A., Falcão, L., Gobatto, F., Novellino, V., Jardim, F., Oliveira, L., Meneguim, T., Amaral, P.J., Borges, F., Teixeira, L., Monteiro R.C., González, G. & González, M., 2016. Incorporação de Estratificações dentro da Seção Evaporítica Utilizando Velocidades e Atributos Sísmicos – (Informe Geofísico da Petrobras – IGP-152 – Petrobras Internal Publication).

Maul, A., Jardim, F., Falcão, L., & González, G., 2015. Observing Amplitude Uncertainties for a Pre-Salt Reservoir Using Illumination Study (Hit-Maps). (77th EAGE Conference & Exhibition 2015) – Madrid, Spain.

Meneguim, T., Mendes, S.C., Maul, A., Falcão, L., González, M. & González, G., 2015. Combining Seismic Facies Analysis and Well Information to Guide New Interval Velocity Models for a Pre-Salt Study, Santos Basin, Brazil. (14th International Congress of the Brazilian Geophysical Society 2015) – Rio de Janeiro – RJ, Brazil.

Meneguim, T., Mendes, S.C., Maul, A., Falcão, L. González, M. & González, G., 2016. Refinamento do Modelo de Reservatórios a partir da Caracterização das Estratificações Salíferas Baseada em Atributos Sísmicos, Pólo Pré-Sal da Bacia de Santos. (48º Congresso Brasileiro de Geologia). Porto Alegre – RS, Brazil.

Oliveira, L.C., Falcão, L., Maul, A., Rosseto, J.A., González, M. & González, G., 2015. Geological Velocity Approach in Order to Obtain a Detailed Velocity Model for the Evaporitic Section, Santos Basin. (14th International Congress of the Brazilian Geophysical Society 2015) – Rio de Janeiro – RJ, Brazil.

Teixeira, L., Gobatto, F., Maul, A., Cruz, N., Gonçalves, C., Laquini, J., 2016. Aplicação da Inversão Sísmica para Modelagam de Velocidades, Fácies e Geomecânica na Seção Evaporítica do Campo de Lula. (XV SIMGEF – Simpósio de Geofísica de Petrobras – Petrobras Internal Publication). Rio de Janeiro – RJ, Brazil.

Yamamoto, T., Maul, A., Born, E., Gobatto, F., Campos, M.T. & González, M., 2016. Incorporação de Estratificações Salíferas Através do Modelo de Velocidade em um Projeto da Bacia de Santos (VII Simpósio Brasileiro de Geofísica – 2016). Ouro Preto – MG, Brazil.