Accurate Velocity Model Refinement through the use of Acoustic Impedance for Evaporite Seismic Facies differentiation of Pre-Salt Reservoir Prospects in Santos Basin

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This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August 2017.

Abstract

Recent advancement in seismic velocity modeling techniques has enabled the development of more accurate seismic processing and imaging.

This paper proposes a novel workflow for seismic velocity modeling of Pre-salt reservoirs prospects based on discrete evaporite seismic facies, acoustic inversion and volumetric seismic attribute differentiation.

Well facies incidence was employed as subside for seismic volume facies tracking. Then, the facies impedance volume and well velocity log are combined to generate a more accurate velocity model.

Results have shown that the proposed methodology produced a better geologically refined velocity model through evaporite seismic facies discretization techniques, when compared with non-discretizing workflows.

Moreover, the proposed workflow enables individual evaporite concentration estimation, velocity correction and calculation of geomechanical parameter range within the salt interval.

Introduction

Currently, Brazilian offshore Pre-salt reservoirs located in the Santos Basin are among the most prominent oil industry areas of interest. These are five kilometers deep reservoirs featuring complex structures over carbonate rocks, such as salt diapirs, stratifications and overhangs.

In recent few years, seismic data processing techniques advancement fueled by computational evolution in regards to multicore architectures and GPU processing. Among those advancements, Reverse Time Migration (RTM) algorithms, anisotropy (VTI – Vertical Transverse Isotropy, TTI – Tilted Transverse Isotropy), reflection tomography, and full-waveform inversion (FWI) are key aspects for optimal reservoir image obtention, enabling confident seismic interpretation.

This paper proposes a novel workflow for velocity model refinement of pre-salt reservoir prospects through the application of acoustic inversion and differentiation of volumetric seismic amplitude data. The process starts by salt layer classified in three deterministic evaporite seismic facies, based on well logs. From the resultant log, respective acoustic impedance (AI) values are determined for each pseudo-facies, employing attribute volume differentiation as a salt class filter. The velocity model components, representing each pseudo-facies, were derived from the extrapolated correlation between AI volume and the well acoustic velocity log.

González *et al.* (2016), Gobatto *et al.* (2016) and Yamamoto *et al.* (2016) incorporated salt stratification analysis to the velocity model, adopting a similar approach as suggested by Maul *et al.* (2015) and Jardim *et al.* (2015). Seismic attribute utilization is proposed by Oliveira *et al.* (2015), González *et al.* (2016) and Maul *et al.* (2016). Meneguim *et al.* (2015) and Meneguim *et al.* (2016) proposed facies utilization as a guide to velocity model development.

This papers proposal is based on the same principles as these previous works; however, it employs facies discretization to differentiate between high velocity salts, low velocity salts and halite. This approach, coupled with AI in addition to seismic attribute utilization, further enhances model accuracy. The proposal, as demonstrated by real well data obtained from Santos Basin, corroborate the salt velocity statistical study conducted by Amaral *et al.* (2015).

Method

The proposed methodology is adapted from the one purposed by Maul *et al.* (2016) presented in González *et al.* (2016), with the introduction of a small novel workflow for evaporite seismic facies generation. The proposed workflow schematic is presented in Figure 1. The parameters for the presented algorithms are described on Table 1.

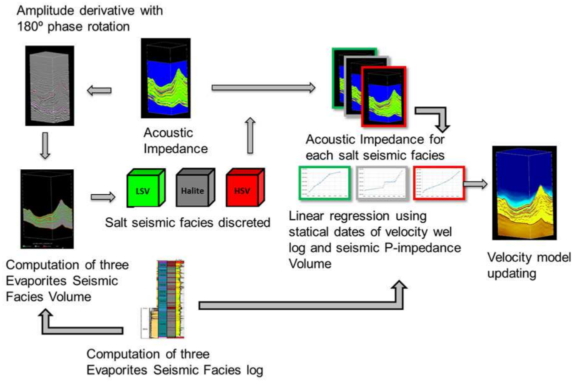

***Figure 1** – Proposed workflow* for evaporite seismic facies generation.

The acoustic impedance volume for the salt layer is calculated using a model-based sparse-spike inversion using full-stack RTM seismic data. The input hybrid low frequency model is calculated merging the AI well log data model with the AI theoretical values model, based on a seismic Hilbert Transform.

Samples with lower seismic amplitude have AI values related to low velocity salts; samples with higher seismic amplitude have AI values related to high velocity salts; and the rest is halite. The procedure for the inversion and acoustic impedance generation is exemplified on Figure 2.

Table 1 – Algorithms parameter descriptions

Variable	Description
α	Salt velocity lower bound
β	Salt velocity higher bound
γ	AI lower bound
δ	LVF maximal amplitude derivative
ε	AI higher bound
τ	HVF maximal amplitude derivative
$AIVol$	Acoustic impedance volume (AI)
$AIVol\_Halite$	Halite AI volume
$AIVol\_HVS$	High velocity salt AI volume
$AIVol\_LVS$	Low velocity salt AI volume
$AmpDev$	First amplitude derivative with +180º phase rotation
SF	Salt facies
VF	Volume facies
Vp	Acoustic velocity log

The first step of the proposed workflow is the computation of three pseudo-facies for a given well section, as depicted in Algorithm 1. The main salts on a velocity log are halite, anhydrite, gypsum, carnalite, tachydrite and sylvite.

Employing a simple conditional algorithm as the premise for salt separation over the acoustic velocity log (Vp), these salts are grouped in three facies: (i) low velocity salts (LVS), carnalite, tachydrite and sylvite, featuring velocities lower than α m/s; (ii) high velocity salts (HVS), gypsum and anhydrite, featuring velocities higher than β m/s; and halite between those extremes.

Gamma Ray (GR), preliminary lithology, seismic amplitude extracted at well position and seismic AI extracted at well position logs are employed as quality control indicators. The generated salt facies log is expected to be closely related to the preliminary lithology log and extracted in seismic volume if the salt section has enough thickness. Low velocity salts are expected to be related to high value of gamma ray.

The second workflow step consists in the utilization of salt facies as a guide for range identification in IA and amplitude derivative +180º phase rotation volumes, as depicted in Algorithm 2. It was noted that the use of inversion did not solve the question related to lateral continuity when analyzing HSV and LSV layers and sometimes over estimating those velocity values.

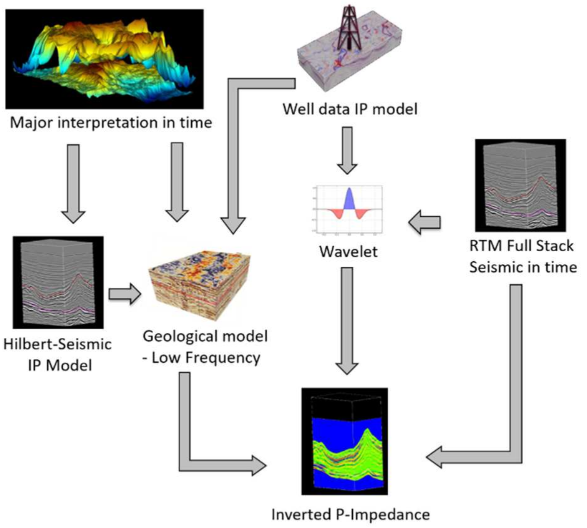

***Figure 2** – Acoustic inversion and acoustic impedance procedures.*

Algorithm 1 – Pseudo-facies computation

```
function $PseudoFaces(Vp)$
  for each $Vp_i$ in $Vp$ do
    if $Vp_i < \alpha$ then
      $SF_i \leftarrow 1$
    else if $Vp_i > \beta$ then
      $SF_i \leftarrow 3$
    else
      $SF_i \leftarrow 2$
  return $SF$
```

Hence, the proposed method solves this issue by utilizing the derivative attribute, which enables to maintain seismic data lateral continuity. In order to keep layer aspect presentation, a phase rotation of +180º is applied to this data. The resulting volume displays a similar thickness between seismic amplitude log and well seismic log. Then, a quality check is performed on data by comparing well facies proportion with well seismic facies at well location, which should be closely related, as shown in Figure 3.

Algorithm 2 – Pseudo-facies range identification

```
function $IdentifyRanges(AIVol, AmpDev)$
  for each $[AIVol_i, AmpDev_i]$ in $[AIVol, AmpDev]$ d
    if $AIVol_i < \gamma$ and $AmpDev_i < \delta$ then
      $VF_i \leftarrow 1$
    else if $AIVol_i > \varepsilon$ and $AmpDev_i > \theta$ then
      $VF_i \leftarrow 3$
    else
      $VF_i \leftarrow 2$
  return $VF$
```

The third step consists in the obtention of each pseudo-facies AI volume by employing the Algorithm 3. Then histograms are constructed for well facies Vp and AI volume for each pseudo-facies. As a quality assurance procedure, outliers detected in AI volume are replaced by nearest neighbor samples.

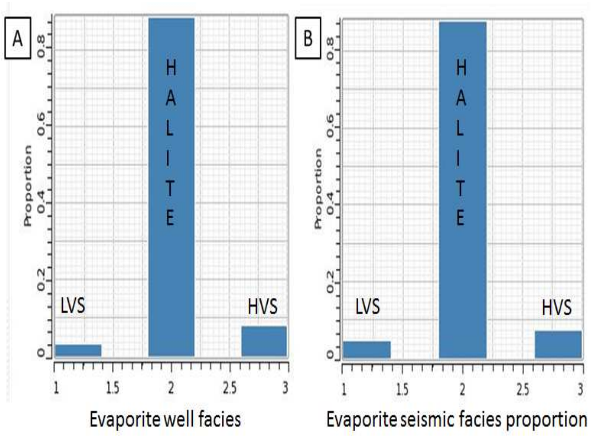

Figure 3 *– Evaporite well facies derived from* ***(A)*** *velocity log and* ***(B)*** *evaporite seismic facies proportion at well location.*

The fourth step consists in the generation of cross-plots followed by second-degree function regression. A cross-plot chart is generated for each facies statistical data (maximum, minimal, median, percentiles) to reflect a larger sample data set for AI volume and well Vp.

That procedure is followed by linear regressions to second-degree polynomial functions. The resulting functions are applied to the AI volumes in order to obtain new velocity volumes. Histograms are used as a quality check measure.

Algorithm 3 – AI volume computation for evaporite seismic facies

```
$\boldsymbol{function}\ ESFacesAIVol(VF, AIVol)$
  $\boldsymbol{for\ each}\ VF_i\ \boldsymbol{in}\ VF\ \boldsymbol{do}$
    $\boldsymbol{if}\ VF_i = 1\ \boldsymbol{then}$
      $AIVol\_LVS_i \leftarrow AIVol_i$
      $AIVol\_Halite_i \leftarrow \emptyset$
      $AIVol\_HVS_i \leftarrow \emptyset$
    $\boldsymbol{else\ if}\ VF_i = 2\ \boldsymbol{then}$
      $AIVol\_LVS_i \leftarrow \emptyset$
      $AIVol\_Halite_i \leftarrow AIVol_i$
      $AIVol\_HVS_i \leftarrow \emptyset$
    $\boldsymbol{else\ if}\ VF_i = 3\ \boldsymbol{then}$
      $AIVol\_LVS_i \leftarrow \emptyset$
      $AIVol\_Halite_i \leftarrow \emptyset$
      $AIVol\_HVS_i \leftarrow AIVol_i$
    $\boldsymbol{else}$
      $AIVol\_LVS_i \leftarrow \emptyset$
      $AIVol\_Halite_i \leftarrow \emptyset$
      $AIVol\_HVS_i \leftarrow \emptyset$
  $\boldsymbol{return}\ [AIVol\_LVS, AIVol\_Halite, AIVol\_HVS_i]$
```

The last step is the merging of each salt velocity volume in a single volume, followed by a moving average filter for lateral smoothing. The refined velocity model can now be used for a next imaging iteration, as schematized in Figure 4.

It is worth to note that this workflow output is an important geomechanical input, as it: (i) facilitates calculation of density and elastic parameter range within salt interior, such as bulk modulus, Poisson coefficient, lambda, elastic velocity, Young module; (ii) helps in the construction of well drilling plans, as high HVS concentrations indicate high density brittle rock, and high LVS concentrations are more soluble than halite, featuring more ductile behavior.

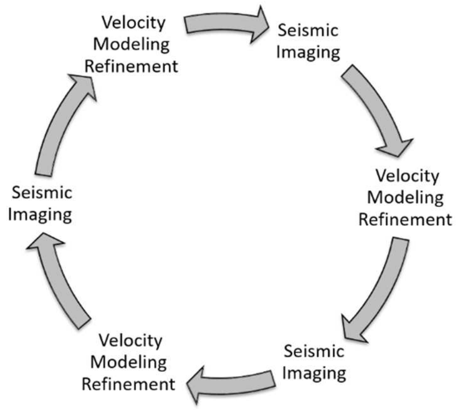

Figure 4 *– Recursive method to iteratively improve the seismic image and the velocity model refinement.*

Case study on Santos Basin

A case study was conducted utilizing data from six wells located in Santos Basin, logs of three of those are exemplified in Figure 5. These wells are geographically distributed, featuring unbiased statistically independent random distributions of stratification thickness. For the processing of this data, the workflow algorithms were calibrated utilizing the constants described in Table 2.

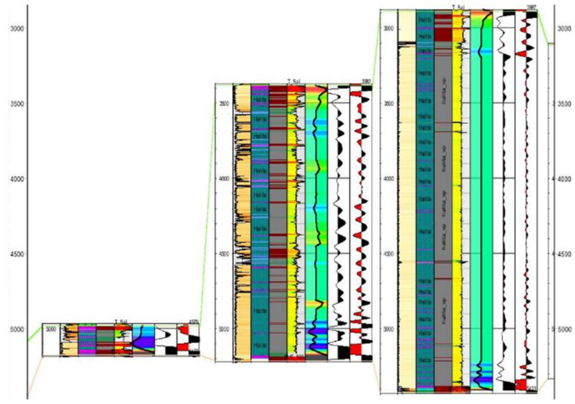

Figure 5 *– Logs for three out of five wells used in this case study. From left to right, the logs are: Gamma ray, preliminary lithology, classified lithology, acoustic velocity, acoustic impedance, seismic amplitude, amplitude derivative attribute with +180º phase rotation.*

Highly stratified (seismic or sub seismic scale) halite predominates in greater salt isopach regions. These thin layers did not impact substantially the global velocity model. In smaller salt isopach regions, there are concentrations of anidrite, which translates in high velocities, which can be verified in the proposed model.

Table 2 – Algorithms variables descriptions

Constant	Value
α	4250m/s
β	4600m/s
γ	$9.34\text{e}+6\text{kg/s}\cdot\text{m}^2$
δ	2.3e+5
ε	$9.8\text{e}+6\text{kg/s}\cdot\text{m}^2$
τ	-3.9e+5

Statistical facies data generated using the second-degree regression for case study are shown in Figure 6. It is worth to notice that both average and median acoustic velocity were found to be closer to 4440m/s, different to the usual values of 4500m/s used for Halite on the initial model calculations.

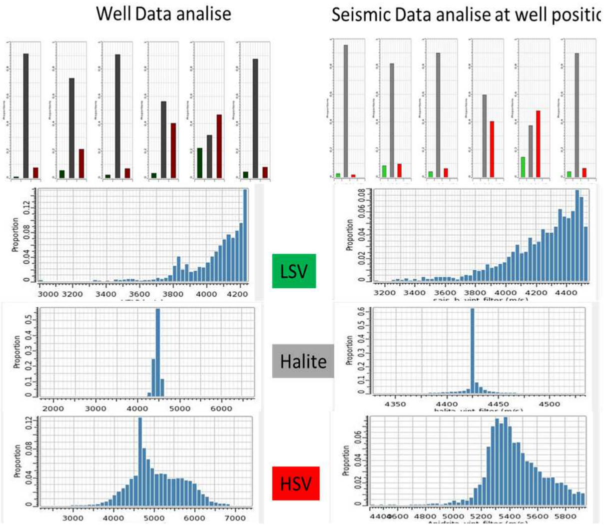

Figure 6 *– Proportion comparison between well evaporite log and evaporite seismic facies extracted at well position. Histograms show velocity distributions in well and AI volume, for LVS, halite and HVS (depicted from top to bottom).*

The authors believe that this is due to traces of lower velocity minerals mixed in halite rocks, but these findings may require further investigation out of the scope of this paper. Equation 1 represents the regression result for low velocity facies, equation 2 represents the regression result for halite and equation 3 represents the regression result for high velocity facies.

The resulting regression equations achieve high enough correlation to satisfy processing requisites. Equation 1 achieves 0.9894 correlation for LVS, equation 2 achieves 0.9881 correlation for HVS, and equation 3 achieves 0.8653 correlation for halite.

The refined velocity model, which is the final output of the proposed workflow before smoothing, is shown on Figure 7. The discretized evaporite seismic facies volume is combined with the AI volume and then used for soluble salt occurrence prediction.

The first velocity model, originary from seismic processing, considers salt layer velocity constant, equal to 4500m/s. Oliveira *et al.* (2015) enhanced this model by incorporating high velocity salt stratification by employing high-contrast seismic amplitude.

Equation 1

$$LVS\_V_{int} = 5 \cdot 10^{-11}\ AIVol^2 - 3 \cdot 10^{-4}\, AIVol + 2992$$

Equation 2

$$Halite\_V_{int} = 7 \cdot 10^{-12}\, AIVol^2 - 7 \cdot 10^{-5}\, AIVol\ + 4466$$

Equation 3

$$HVS\_V_{int}\ = 4 \cdot 10^{-10}\, AIVol^2 + 9{,}7 \cdot 10^{-3}\, AIVol - 5001$$

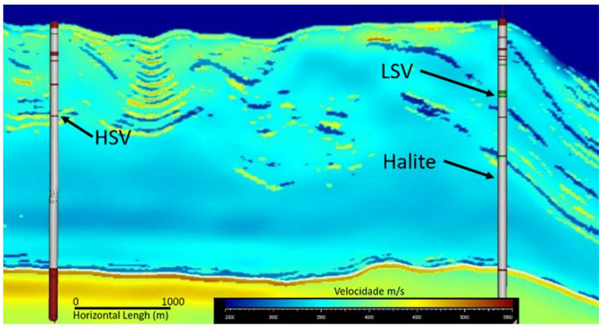

Figure 7 *– Refined result of accurate velocity model refinement through the application of acoustic Impedance towards evaporite seismic facies.*

Araújo *et al.* (2016) demonstrated that seismic reprocessing of this type of input data utilizing RTM, anisotropy (TTI), reflection tomography and FWI, provides many advantages over the previous method. For instance, the incorporation of HVS on this process geologically oriented reprocessing phases. Another merit of this reprocessing was to demonstrate the existence of super-estimated regions on the initial velocity model. This reprocessed data was used as input for this paper proposed workflow, Figure 8.

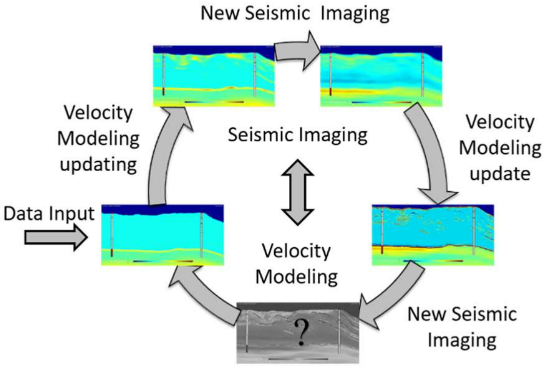

Figure 8 *– Recursive method for accurate the velocity modeling to update seismic in terms of quality, lateral and depth positioning.*

Conclusions

This paper proposed and presented a case study from the Santos Basin of a novel workflow for velocity model refinement of Pre-salt reservoir prospects through the application of acoustic inversion and differentiation of volumetric seismic amplitude data.

Salt facies are employed as a guide for range identification in IA and amplitude derivative +180º phase rotation volumes.

Evaporite seismic facies discretization accomplishes more accurate geological velocity modeling, when compared with non-discretizing workflows. Moreover, the proposed workflow and accompanying methodology enables seismic evaporate facies thickness maps construction.

It is also possible to estimate evaporate occurrence individually. Hence, the proposed workflow helps in the construction of a well drilling geological prevision frame.

The workflow output is an important geomechanical input that facilitates calculation of volumetric and elastic parameters within salt layer, aiding substantially in the construction of well drilling plans.

Acknowledgments

The authors would like to thank Petrobras and Paradigm for giving the support, time and data for this research, as well as for allowing the publication. We gratefully acknowledge the helpful input and generosity of Ricardo Rosa, Rui Sansonowski, Igor Aragão, João Rosseto, Sergio Araujo, Axel Geisslinger and Leonardo Oliveira.

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