Rock Physics and Seismic Inversion to identify stratification within salt section supporting velocity, facies modeling and geomechanical analysis

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Abstract

Challenges in oil producing from Pre-salt field go beyond reservoir characteristics. Pre-salt reservoir is located in ultra-deep water. They are carbonates, most formed by microbiolite, coquina, volcanoclastic, with vertical and lateral heterogeneity. Fluid in these rocks may vary from low to high CO2 content with large differences related to gas-oil ratio. Moreover, to reach these reservoir, up to 3000 m of evaporite section must be drilled.

Evaporites are particular rocks resulting from chemical precipitation in a restricted environment and high rate of water evaporation. Under high pressure and overburden, evaporite rocks impose drilling challenges. Under these circumstances, salt formations have mobile nature. In a short time, due to higher deformation rate than sedimentary rocks, well stability and safety are unsteady affecting well bore stability. Creep behavior of salt rock can lead to hole closure and borehole collapse. Undoubtedly, to achieve the goals of development and monitoring of these field through a well drilling campaign, salt rock must be known.

To achieve this aim, we purpose in these paper a workflow which takes into account geological, well log and seismic information. Flowing steps are purposed and accomplished: get rock physics relation from well log information; perform seismic inversion in order to get elastic property; derive probabilistic facies through Bayesian classification and, at length, make quantitative seismic interpretation of these data with geological, geophysical and engineering integration.

Introduction

Salt mineralogy is an important information at hand when drilling through evaporite rocks. Chlorite and sulphate salts, such as Tachyhydrite ($CaCl_2.2MgCl_2.12H_2O$) and Carnalite ($KCl.MgCl_2.6H_2O$), have a higher creep strain rate when comparing to Halite (NaCl). Tachyhydrite has two orders of magnitude creep strain rate than Halite. When intercalation of mobile rocks occurs in the thick layers of halite, many operation problems have been reported as stuck pipe and collapse borehole (Costa et al., 2010). Anhydrite ($CaSO_4$) is found among evaporite rock but it is considered as immobile.

Salt rocks have a great range of velocity. Laboratory measurement estimate 6000 m/s for anhydrite and 3200 m/s for silvinite (Mavko et al., 2009). Gobatto et al. (2016) show it is important to identify salt stratification to build velocity model. By spatially identifying the salt rock types, velocity models were refining, happening Pre-Salt reservoir top to be adjusted and correct predicted for new wells. Results from modelling seismic amplitude with salt stratification show a better match with real data (Jardim et al., 2015; Maul et al., 2015), regarding illumination uncertainty. Furthermore, identifying different salt rock type within thick layer of halite has been proved to be useful for seismic processing, for initial models for tomography and full waveform inversion.

Empirical equation from well log analyses show elastic properties have a good correlation between themselves. Through rock physics analysis, these equations correlate Young Modulus, Density, Compressional, Shear Velocity and Acoustic Impedance. Afterwards, these equations were applied to output data from seismic inversion in order to get a 3D elastic properties cube.

Seismic Facies was performed using the concept of Statistical Rock Physics (Murkeji et al., 2001). In this workflow, well logs and geological knowledge give us *priori* information and probabilistic elastic properties for each facies. Through Bayesian inference, 3D probabilistic cubes for each facies were performed.

First Approach: seismic amplitude

First approach identifying salt rock types were based on seismic amplitude. Falcão et al, (2014) propose an incorporation of salt stratification in seismic velocity in order to respect the geological characterization of salt layers. Regions within evaporate section show seismic reflections which were associated to intercalation of Tachyhydrite, Carnalite, Anhydrite, Silvinite (mobile salt) within the thick layer of Halite.

Oliveira et al., (2015) applied workflow suggested by Falcão et al., (2014) and compared salt proportional facies in well log to what is derived from seismic data. They concluded that the highest amplitudes, at most, were related to anhydrite, however, if the lowest amplitude were related to mobile salt then it would be overestimated by seismic data.

Seismic amplitude is a quick approach to identify salt stratification and spatially detects its occurrence. However, synthetic seismic data shows that mobile and immobile salt may produce the same effect in seismic amplitude. To illustrate how it happens, we will use European definition of seismic amplitude: it is positive if the change of acoustic impedance varies from low to high amplitude, and negative, otherwise. To understand this effect in seismic data, we model an example of Anhydrite and Tachyhydrite embedded in a layers of Halite. The layers of Anhydrite and Tachyhydrite is about 25 m so tuning effect can be disregarded.

Figure 1 show a layer of Anhydrite and Tachyhydrite embedded in a layer of Halite. it is a situation commonly found in evaporate rock above Brazilian Pre-Salt. We modelled acoustic impedance 6000 m/s g/cc, 9300 m/s g/cc and 15000 m/s g/cc for Tachyhydrite, Halite and Anhydrite, respectively. These values represent measurements usually found in well log data. Synthetic seismic was created using a zero phase wavelet with dominant frequency about 25 Hz. Both Anhydrite and Tachyhydrite embedded in a Halite layers yield positive and negative amplitude response.

The example given by Figure 1 indicates that seismic amplitude data should not be the better choice for salt discrimination, though it is helpful for a first approach. Therefore, instead of using seismic amplitude, we performed seismic inversion in order to derive acoustic impedance. Figure 2 models synthetic traces created by layers of Anhydrite–Halite-Tachyhydrite, as shown in Figure 1, and seismic inversion proceed with this traces. It is clear that salt can be discriminated by acoustic impedance value.

Rock Physics Empirical Relations

In an isotropic media, if two elastic properties are known, we can derive other properties. Unfortunately, not all elastic properties are measured in salt layers. It may happen for tool complications or low cost plans to cut well log acquisition. However, we know that it is important for geomechanical modelling to know Young Modulus, Density and Poisson Ratio measurement, as well as, Shear Velocity for seismic inversion and AVO study.

Yan et al, (2016), through laboratory measurement, indicated that stress effect on compressional velocity of halite is not significant. The stress effect on rock velocity is controlled by their poroelasticity. Porosity on salt rock is almost irrelevant. In fact, through well log analysis, changes in salt velocity may be associated to proportional of salt rock type and its composition within limits of well log tool detection than to stress effect.

Regularly, compressional sonic wave is required in well log prospect. So, in order to achieve elastic properties required for geomechanical modelling and seismic inversion, rock physics empirical relations were obtained for evaporite rocks.

In case of only compressional wave is present, density and shear velocity must be derived from this elastic property to create acoustic and shear impedances. Figure 3 show a crossrelation between density and compressional velocity It is possible, with a high confidence, to infer a second degree equation estimating density in salt rocks. Same approach is used to estimate shear velocity from compressional velocity. Equation 1 and 2 show the existing relation between density, shear velocity and compressional velocity. Figure 4 and compares well log to modelled well log when equation 1 was applied.

$$\rho = 2.1395\,x\,10^{-7} v_p^2 - 1{,}394\,x\,10^{-3} v_p + 3.959 \quad (1)$$
$$v_s = -2.40776\,x\,10^{-4} v_p^2 + 2.7719 v_p - 5099.61 \quad (2)$$

Density and velocity are measured in g/cc and m/s, respectively. A correlation coefficient is 0.90 for density and 0.91 for shear velocity.

Geomechanical Modelling is an essential tool to support and to make decision in a lifetime of reservoir production. It’s related to well stability while drilling, fracture and fault activation, compaction and subsidence prediction. Elastic properties such as density, Young Modulus and Poisson Ratio are needed. Young Modulus could be generated by combining equation 1 e 2. However, in order to minimize error between real and modelled data, a relation was established between Young Modulus and Compressional Velocity. Figure 5 shows a crossrelation between Young Modulus and compressional velocity; Figure 6 compares real well log to modelled well log when equation 3 was applied.

$$E = 4.8813\,x\,10^{-6} v_p^2 - 1.9778x\,10^{-2} v_p + 22.3112 \quad (3)$$

Young Modulus is measured in GPa. The correlation coefficient for equation 3 is 0.90.

Elastic Properties from Seismic Inversion

Velocity Modelling can be refining using seismic inversion, well log and information from seismic processing. Well and seismic information are coupled using geostatistical techniques. Gobatto et al., (2016) argue that geological velocity model can be useful for illumination study and seismic processing.

Getting compressional velocity from seismic inversion is a trick problem. It is shown that density data brought from seismic inversion is not trustable, in other words, the reliability of compressional velocity is low. With the purpose of overcoming this problem, we propose to get compressional velocity from a relation between compressional velocity and acoustic impedance. A third degree equation is useful to link properly these properties as show in equation 4 (cc 0.90). Figure 7 compares velocity modelled from velocity from sonic log.

$v_p = 2.342 \, x \, 10^{-9} I_p^3 - 8.51 \, x \, 10^{-5} I_p^2 + 1.1577 I_p - 755.57$ (4)

If one wants to perform geomechical modelling, Young Modules is required. For same reason velocity data from seismic inversion is not reliable, Young Modulus cannot be a trustful parameter from seismic inversion. Density is needed. However, as velocity data, it is possible to model it from acoustic impedance. Banik et al., (2010) faced the same problem for unconventional reservoir and overcame this problem showing these two properties is highly correlatated. Figure 8 illustrate a crossplot Young Modulus and Acoustic Impedance. A third degree equation is fitted and applied, with cc 0.95 (equation 5). Figure 9 compared Young Modulus modeled by acoustic impedance to calculated one in well log data. It is possible to see the high agreement between curves.

$E = 2.340 \, x \, 10^{-11} I_p^3 - 8.080 \, x \, 10^{-7} I_p^2 + 1.350 x \, 10^{-2} I_p - 41.507$ (5)

At last, one more parameter is desired: density. We purpose two approach which lead to almost same result. First one consists in dividing acoustic impedance by velocity obtained from equation 4. Second one is to model it from acoustic impedance. We keep same analysis and purpose a third degree equation. Results from application of equation 6 are show in figure 10.

$\rho = -1.6845 \, x \, 10^{-12} I_p^3 + 5.325 x \, 10^{-8} I_p^2 - 4.003 x \, 10^{-4} I_p + 2.522$ (6)

On the other hand, as density may be inferred divided acoustic impedance per modelled velocity, it is practical to infer velocity by dividing acoustic impedance to density. It may be done and results, as long as modeled equation is a good approximation, will be very similar. We assume and know that all models are wrong however they may be useful. For our proposal, they fit well in study.

Seismic facies: Bayesian approach

Bayesian classification is a workflow which generates facies probability from elastic properties obtained in seismic inversion. Using Bayes Theorem, seismic and geologic information are combined. This technique builds probability density function from facies, elastic properties and priori information.

Probability density functions are applied to seismic inversion output, sample by sample, given a posteriori probability cube for each facies. Uncertainty analysis can be obtained from this procedure due to probabilistic approach. Also, most probable facies can be derived.

Several salt rock type may be found in Santos Basin such as Silvinite, Tachyhydrite, Carnalite, Halite, Anhydrite and others. These salt rocks have different mean values of acoustic impedance and, at log scale, they may be discriminated. Nevertheless, seismic data is an indirect method of measurement and signal to noise ratio must be taken into account. Therefore, although well log data show different mean values for Silvinite, Tachyhydrite, Carnalite, they all are grouped into a mobile salt class. We keep the description for halite and anhydrite.

Bayesian classification was performed and most probable facies and probability cube for each one of them were generated.

Figure 11 show probability cube of mobile salt in a seismic section going through four well path. Salt facies is represented in well path in order to observe the correlation between predicted seismic facies and well log information, using in Bayesian classification. It it possible to note a good match between seismic information and well log data: high values of mobile salt probability in seismic data correspond to occurrence of mobile salt in well log data.

It is important to state that seismic inversion was a key to achieve to salt facies. As shown by synthetic analysis, seismic amplitude is dubious to identifying salt facies. We cannot associate positive and negative amplitude to an occurrence of a salt rock type.

Applications: velocity, geomechanical modelling

Velocity model can be refined in order to get more reliable information for depth positioning, as initial input for full both waveform inversion or tomography for seismic processing.

Rock physics analysis for salt rock shows that velocity and acoustic impedance has a high correlation. So, as an alternative of using mean velocity value of seismic facies (Meneguim et al., 2015), we purpose a third degree polynomial equation to derive compressional velocity from acoustic impedance. This cube is, then, used to be combined with velocity data from seismic processing in the evaporite section. Figure 12 show the incorporation of salt stratification.

Geomechanical modelling requires information on elastic properties to be performed. As density is not a consistent data from seismic inversion, property as Young Modulus cannot be achieved by manipulating mathematically seismic volumes. To overcome this situation, we purpose a third degree polynomial equation to derive Young Modulus. The result was coupled to geomechanical Simulator.

Costa et al., (2010) described salt creep rock behavior by experimental analysis. Tachyhydrite creeps about 107 times faster than Halite and 2,7 times faster than carnalite. Property of mobile salt can be taken into account by a spatially characterization of seismic facies. Reservoir compaction due to production inducts different creep behavior in salt layer. Geomechanical simulation indicates subsidence in top of salt section and in sea floor due to reservoir production. Mobile salt is associated to this phenomenon. Figure 13 illustrates the occurrence of vertical displacements in top of salt layer.

Operation problems have been reported such as stuck pipe and collapse. The deeper we drill, creepier behavior is expected for salt rock. Figure 14 illustrates a stuck pipe related report for well A. It took place in a presence of mobile salt (tachyhydrite) in a depth range between 4500 to 4550 m down sea level. As Tachyhydrite and Carnalite shows a creepier behavior than Halite and Anhydrite, it is important to predict its occurrence before drilling.

Conclusions

Many challenges have been faced in development of Brazilian Reservoir Pre-salt which go beyond reservoir properties. Before reaching reservoir top, an evaporite section which can vary from few meters to 3000 m, must be drilled.

Due to low cost plan or log tool complications, density, p- and s-sonic may not be found in well information. Using rock physics empirical relation, we purposed to derive s-sonic, density and Young Modulus from p-sonic measurement. These data were useful as input for 1D analysis for seismic inversion and geomechanical studies.

Reservoir modelling requires physical information in a spatial representation. Seismic inversion provided acoustic impedance information in three dimensional. Applying rock physics empirical relation, information from well log was distributed spatially. Compressional velocity, Density and Young Modulus were valuable for velocity and geomechanical modelling.

As Salt Rocks as Halite, Carnalite, Tachyhydrite and Silvinite have plastic behavior under deviatoric stress. Tachyhydrite creeps much faster than halite. Issued of drilling has been reported in mobile salt layers. Identifying these salt rock (Tachyhydrite, Carnalite, Silvinite) would avoid stuck pipe and collapse. Bayesian classification on seismic data was performed and found helpful in recognizing them before drilling.

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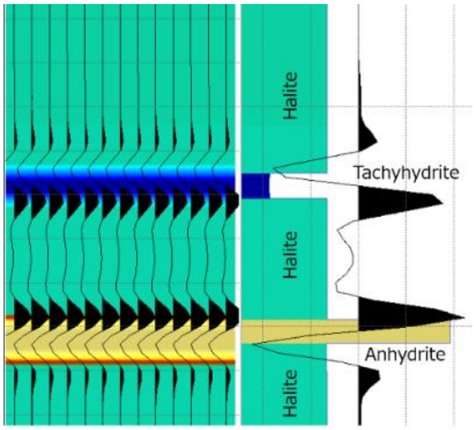

Figure 1 - A layer of Anhydrite and Tachyhydrite embedded in a layer of Halite. Positive and negative amplitudes take place in both cases.

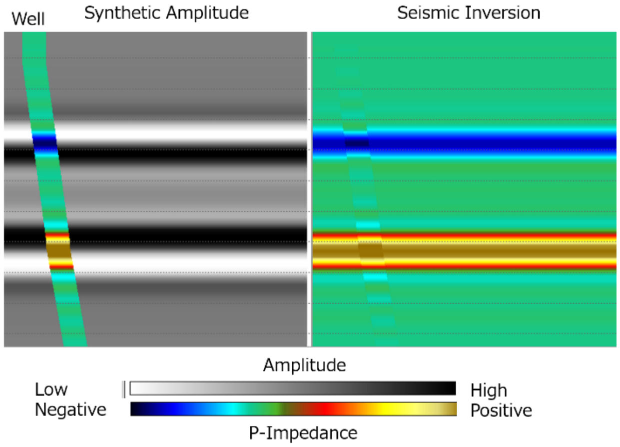

Figure 2 - Synthetic model traces created by layers of Anhydrite–Halite-Tachyhydrite. Seismic inversion was performed to discriminate different salts.

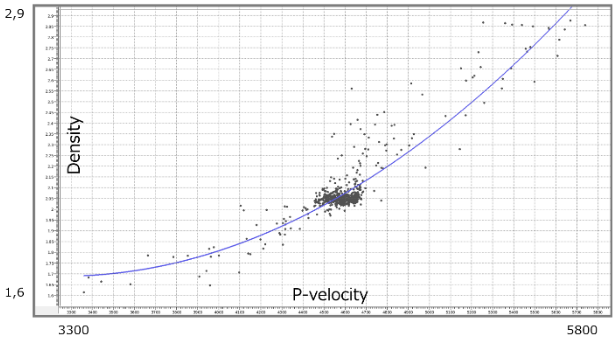

Figure 3 – Density and P-velocity relation in salt layer.

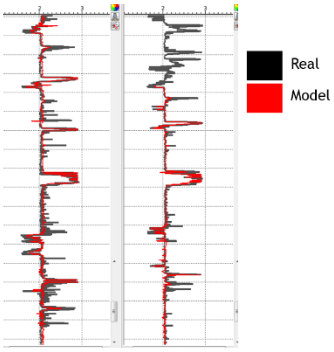

Figure 4 – Well log view comparing two wells with density log acquisition (black) and density modelled from P-velocity

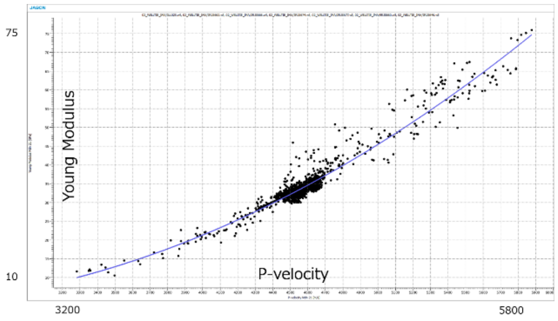

Figure 5 – Young Modulus and P-velocity relation in salt layer.

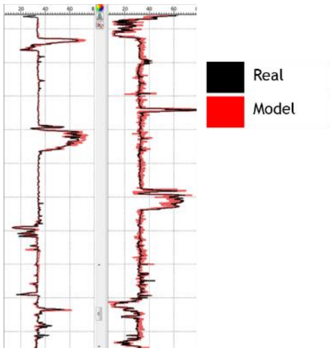

Figure 6 – Well log view comparing two wells with Young Modulus derived from log acquisition (black) and density modelled from P-velocity (red)

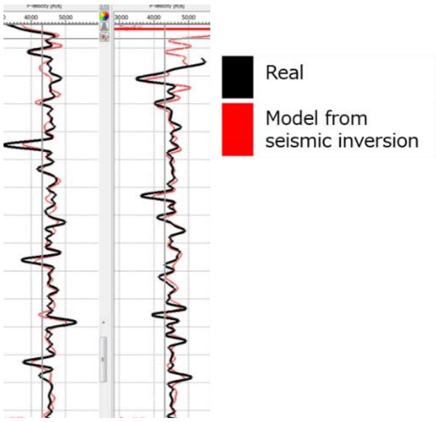

Figure 7 –Well log view comparing two wells with compressional velocity from log acquisition filtered at seismic scale (black) and velocity modelled from seismic inversion.

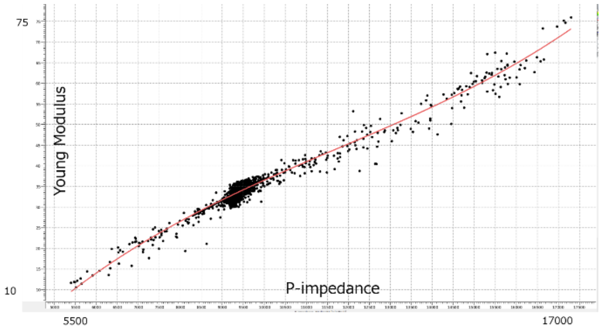

Figure 8 – Young Modulus and P-impedance relation in salt layer.

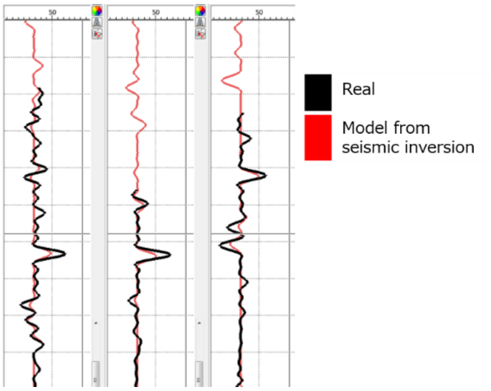

Figure 9 - Well log view comparing three wells with Young Modulus calculated from log acquisition filtered at seismic scale (black) and velocity modelled from seismic inversion (red).

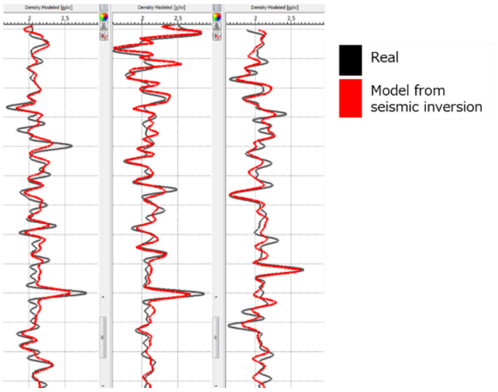

Figure 10 - Well log view comparing three wells with density from log acquisition filtered at seismic scale (black) and density modelled from seismic inversion (red).

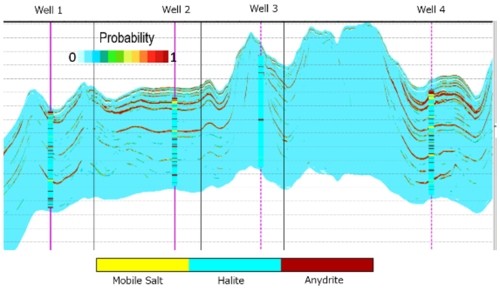

Figure 11 - Probability cube of mobile salt in a seismic section going through four well path

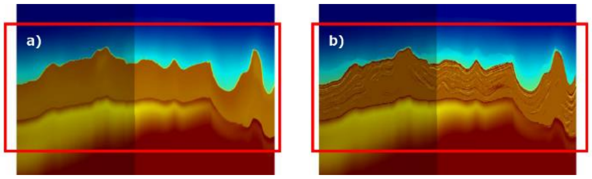

Figure 12 – Incorporation of salt stratification in velocity modelling. a) velocity from seismic migration; b) refined velocity modelling with salt stratification.

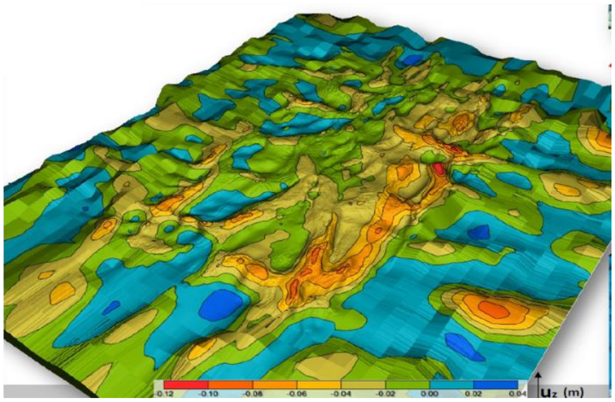

Figure 13 – Vertical doisplacement in top of salt layer taken in account creep behavior of different rock salt type.

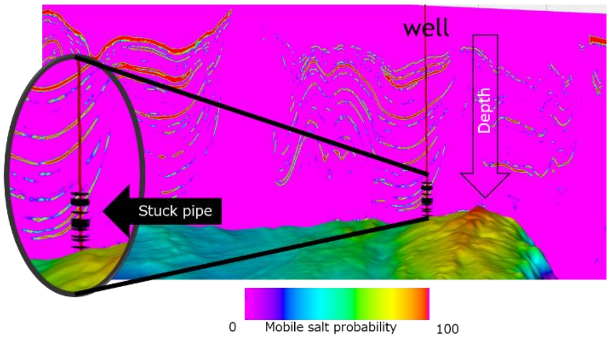

Figure 14 – Probability cube of Mobile Salt. Stuck pipe was related to Mobile Salt which has higher creep ratio compared to Halite.