Using rock physics and full elastic modeling to seismically model complex lithologies

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Summary

Previous work by Nasser and Sinton (2011) showed how it is possible to combine rock physics models and elastic simulations to make better decisions concerning seismic acquisition and processing, as well as to help communicate complex geophysical concepts to decision makers. That work focused purely on clastic geology was recently extended to more complex geologies that include clastics, carbonates, evaporites and mixed facies. The goal of this work is to better understand the limits of available seismic data for characterizing a subsalt carbonate reservoir in terms of resolution, image quality, noise attenuation and hence rock and fluid peroperties.

Introduction

Data used for this study is from offshore Brazil in an area with pre-salt reservoir discoveries. Wells in the area were used to build a rock physics model that correctly predicts elastic properties for clastics, carbonates, evaporites and lithologies of mixed facies. Seismic anisotropy was taken and introduced into the models using values reasonable for the area of interest. Seismic attenuation was added as well to obtain reasonable primary to water layer multiple amplitude ratios.

Well data suggested that the target zone was vertically complex and might be laterally complex as well. Decision makers wanted to understand in quantitative terms the value of reprocessing the current data or the acquisition of a new seismic data. Seismic simulations, processing and imaging were deemed the best methods to define realistic limits of resolution for defining the smaller scale features.

Rock physics modeling

The Differential Effective Medium (DEM) scheme provides a tool to calculate the effective bulk and shear moduli for different pore types (Berryman, 1992; Mavko et al., 2009). This scheme simulates porosities in a composite of two phases by incrementally adding small amount of pores (phase 2) into the matrix (phase 1). Following Xu and Payne's (2009) model for carbonates extended from Xu-white (1996) model for clastics, we can mix any combination of minerals present in the rock using Voigt-Reuss-Hill averages to simulate a solid frame of sandstones, carbonates or both combined. Moreover, the total pore space can be divided into four components: clay-related pores, stiff pores (vuggs), reference pores (interparticle), and cracks. The clay-related pores are added first followed by the three other pore types using the DEM scheme to get the dry effective bulk and shear moduli. Finally, Gassmann's fluid substitution is performed and the elastic response of the saturated rock is calculated.

2D elastic model

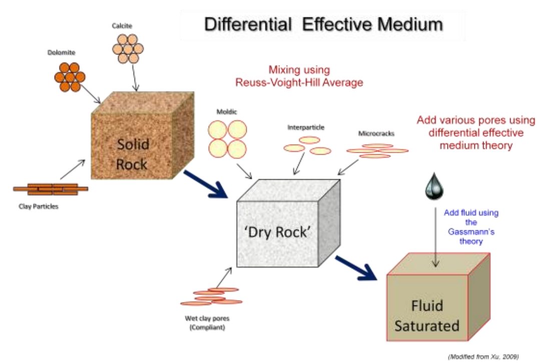

Figure 1: Rock Physics workflow for calculating the bulk and shear moduli of a dry rock, adopted from Xu & Payne, 2009.

A very detailed 2D elastic model was created at near well-log sampling levels so that small scale features found in wells could be captured. Figure 2 depicts the range of facies in the model, which includes shale, sandy shale, limy shale, sand, limy sand, low porosity limestone, dolomite, halite, anhydrite, and high porosity limestone.

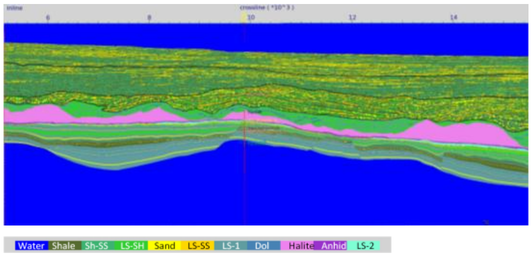

Figure 2: 2D facies model.

The facies distribution was derived from a combination of well information and seismic character, although it would also be possible to use some type of seismic inversion to drive at least part of the facies definition. Well data was used to derive the "background" shale velocity as a function of depth below water bottom. A rock-physics model based on well data in the area was used to convert the facies distribution to vertical compressional velocity (V_p), vertical shear velocity (V_s) and density (ρ).

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Thomsen's (Thomsen, 1986) parameters (δ and ε) as well as seismic attenuation estimates were available as part of seismic processing projects in the area.

We followed the method described by Nasser and Sinton (2011) for deriving a background (shale) elastic model. In this case the background model was divided into zones where the facies were either purely clastic, mixed clastic and carbonate, or purely carbonate. The zones were defined by the interpreter following the geologic trends in the area. Attenuation was added to the model based on comparisons with seismic data.

Seismic simulations

Simulated 2D shots were computed with the elastic model using a 2-way, elastic finite difference algorithm (Levander, 1988; Juhlin, 1995). The sample shot shown in Figure 3 has many characteristics of a typical field shot acquired in the area of interest, although the shot was computed without free surface multiples. One can see a strong effect on seismic reflection character (generally lower frequency content) at the target levels between 3-5 s. Figure 4 compares a shot with and without free surface multiple reflections. The difference in phase between the two shots is caused by the presence or lack of the free surface. Multiple reflection strength is much greater than the primary strength and multiples retain high frequencies. This is a well understood effect but is rarely considered when conducting modeling projects for acquisition and processing design. Frequency spectra for zones near the water bottom reflection (blue rectangle in Figure 4) and target zone (green rectangle in Figure 4) quantify the amount of frequency loss due to attenuation.

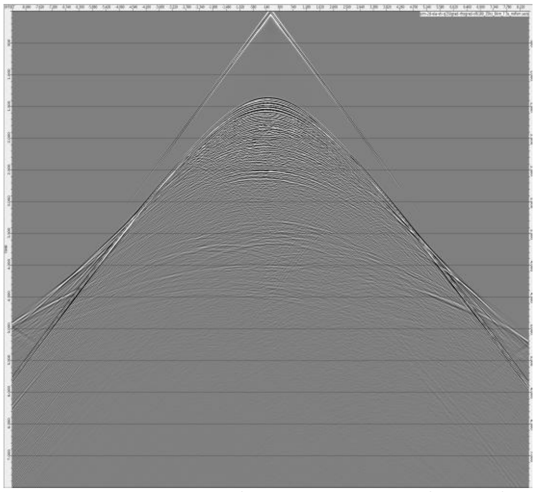

Figure 3: Example shot for Q=150 and no free surface multiples.

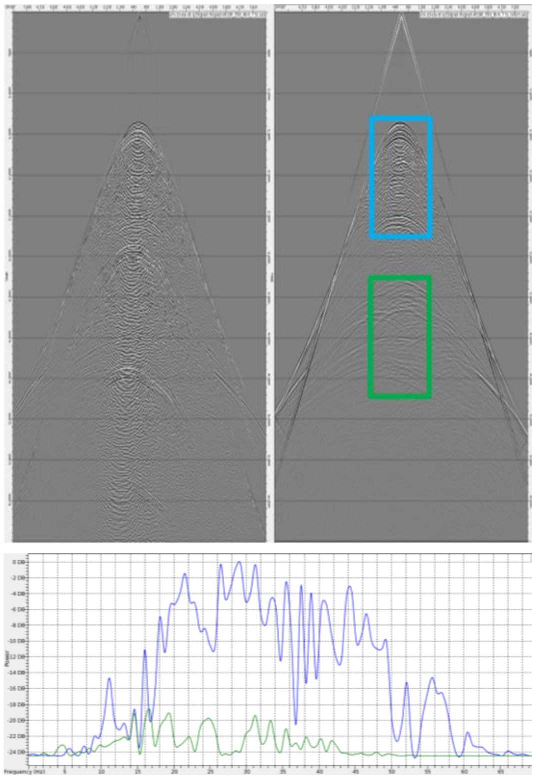

Figure 4: Top - Shot for Q=150 with free surface multiples (left) and without free surface multiples (right). Bottom – Frequency spectra for the analysis windows indicated by the blue and green rectangles.

To test the Q model fit to real data, shot-profile wave-equation depth migration (WEM) was used to create an

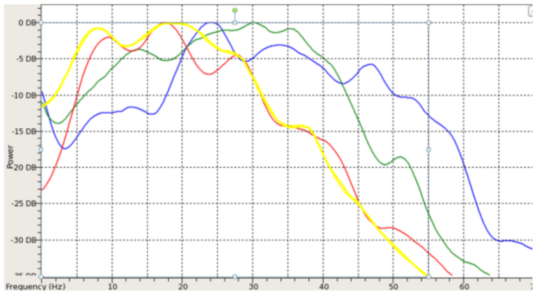

Figure 5: Normalized frequency spectra for field data (blue and red) and simulated data (green and yellow). Blue and green curves were computed for a window around the water bottom. Red and yellow curves were computed for a deep window.

image with the simulated shots that could be compared to a depth image of the field data. The WEM migration used the VTI velocity model without the Q property, effectively ignoring the dispersion effects of the Q model inherent in the simulated shots. Spectra were computed on traces converted to time using the velocity model of the simulated shots. Figure 5 compares field and simulated data frequency spectra computed within two windows: near the water bottom and at a target zone several kilometers below the water bottom. Comparing spectral shapes was deemed an adequate measure of the Q model fit.

One of the realities of an attenuating media is it ideally requires the inclusion of attenuation in the migration velocity model to produce an accurate image. Since attenuation introduces dispersion by making velocity frequency dependent it must introduce vertical shifts relative to a non-attenuating media, thus, non-attenuating migration will produce an image that over estimates reflection depth as well as having time/depth variable phase inaccuracies. Since most commercially available imaging algorithms do not include Q as part of the velocity model an industry standard solution to this problem is to apply a Q correction to the preprocessed data prior to imaging. Examples of image gathers computed from elastically simulated shots where the velocity model included both VTI anisotropy and Q attenuation are shown in Figure 6 with and without the pre-imaging Q correction commonly used in the industry (Sherriff and Geldart, 1982). The red line in Figure 6 helps indentify small but measurable depth shifts between the two sets of image gathers. The image gathers on the right were subjected to a pre-image constant Q=150 correction affecting both amplitude and phase.

Discussion

The seismic examples show that the Rock Physics model for mixed lithologies provided the mechanism by which seismic reflection information could be converted to elastic properties that produce very realistic looking simulated seismic information. Understanding the limits of seismic resolution was one of the most important topics of investigation for this project. Adding attenuation to the elastic simulation clearly demonstrates that it is the largest factor controlling resolution at the target level for a fix spectral output for the seismic source.

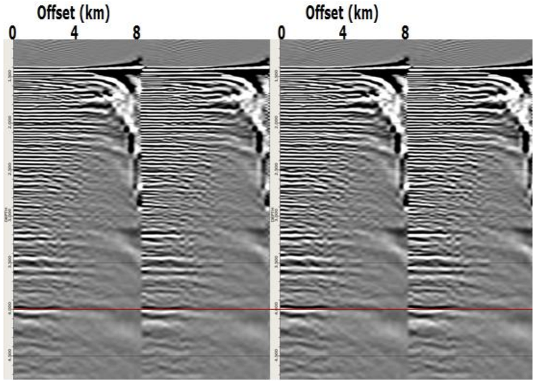

Figure 6: Common offset WEM image gathers without pre-imaging Q correction (left) and with pre-imaging constant Q correction (right).

Given the reasonably good match between the real and simulated spectrums within the deeper window the Q model employed to simulate shots seems adequate for the purposes of predicting resolution at the target zone. On the other hand the spectral agreement at the water bottom could be improved but only at the cost of significantly increasing the cost of the simulation. Thus, it was decided to accept the degree of fit at the water bottom since it would not necessarily influence decisions at the target zone.

Adding attenuation to the simulation model provoked a thought on how to handle the Q correction because imaging the uncorrected shots without a correction for Q results in slightly greater depths. Although not demonstrated in Figure 6, the constant Q pre-imaging correction reduces depth errors but does not eliminate them. It is hypothesized that the migration algorithm must take Q into account during imaging. Further tests are in progress which should demonstrate this conclusively.

Depth error caused by not taking Q into account during imaging might cause one to lump the error into an estimate of the VTI parameters. Thus there could be some inherent ambiguity between determining the velocity anisotropy and attenuation properties. More investigations are required to understand how one could separate the two effects.

Conclusions

Modeling methods introduced by Nasser and Sinton (2011) were successfully extended to a complex, mixed facies geologic environment to address seismic acquisition design, seismic processing decisions and interpretation issues such as resolution limitations. Attenuation is identified as a 1st order effect controlling one’s ability to use higher frequencies within the target depth range.

Further work is required (and planned) to resolve issues with Q and velocity anisotropy.

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EDITED REFERENCES

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