Combining seismic data preconditioning, AVO inversion and geometrical attributes for high resolution reservoir delineation

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Abstract

We show how conventional AVO inversion can be pushed further as a reservoir delineation tool, if viewed as part of larger workflow, which includes gather preconditioning, to increase signal-to-noise ratio and vertical resolution of the seismic data, in addition to an automatic detailed stratigraphic interpretation for reliable background model building. Our strategy includes carrying the whole inversion in a form independent on the low frequency information to retrieve only variations of P and S-wave impedances and density. The estimated models are then combined with their corresponding background model derived using the horizon cube technology. Application to an offshore marine data set illustrates the advantages this methodology brings to prospect evaluation.

Introduction

The main goal of reservoir delineation is to provide spatial distribution of reservoir bodies together with a fluid sensitive attribute to reduce risk associated with drilling. This task requires availability of 3D prestack migrated volume and additional well-log data coming from appraisal wells.

It is now well known that to achieve improved resolution it is essential to perform special target oriented post processing workflows for gather conditioning prior to inversion (see e.g., Singleton, 2009). Untreated propagation effects, noise and seismic processing related artifacts usually locally degrades the quality of seismic data. Seismic data precondition workflows may include 3 main stages, consisting of data denoising for both random and coherent noise, frequency dependent attenuation compensation and residual moveout correction. This lends improved signal-to-noise ratio and higher vertical and lateral resolution to the output data, making significant impact not only for inversion, but also for interpretation and play analysis. Additionally, working with aligned gathers allows for more offsets to be included in the AVO inversion, contributing to improve the quality of shear wave velocity and density estimation.

Multispectral transforms are particularly appropriated to represent seismic data traces in the time-frequency domain, preserving local character of the signal as expression of geological features in the subsurface. Braga (2011) developed techniques for attenuation and dispersion compensation and for residual moveout correction, both based on the 1-D wavelet transforms. These techniques have been applied to prospect delineation in real data resulting in accurate seismic data interpretation, as well as high quality of inverted elastic parameters, providing a reliable fluid indicator for the area.

An important issue in inversion is how to handle the missing low-frequency end of the spectrum. Our approach is to carry the inversion completely independent of the low frequency background model or any other well derived information, considering that this information is actually not required to obtain high frequency variations of elastic properties (Vp, Vs and density) with respect to a smooth background, using existing forms of linear approximations to Zoeppritz equations. The inversion is carried with conventional AVO reflectivity inversion followed by a model based impedance inversion with adaptive wavelet (Oliveira, et al., 2009). The resulting volumes of elastic property variations are then combined with their respective background models, which are derived from the combination of well-log measurements and seismic geometrical attributes. High-end methods for geometric attributes, such as the horizon cube (de Groot et al, 2010), based on dip steering estimation technique, provide exceptional quality of interpolated volumes of well-log derived properties.

In this paper we will cover the method of multispectral filtering and data enhancement, give detailed step-by-step presentation of the complete workflow for high resolution prospect analysis and discuss the impact of the results.

Seismic data preconditioning by multispectral methods

Figure 1 illustrates the seismic data preconditioning workflow, consisting of three main stages: i) noise suppression, ii) gather alignment and iii) data enhancement. For the noise suppression part of the workflow, we use an out of shelf multiple elimination by high resolution Radon transform. We concentrate our development effort in data enhancement by inverse Q filtering and gather alignment by residual moveout correction. The continuous wavelet transform (CWT) is well suited as implementation framework for such time varying operations. Wang (2006) and Margrave et al. (2011) develop data enhancement techniques using the Garbor transform. The Garbor transform is a particular type of windowed Fourier transform, thus allowing for time-frequency spectral analysis. In this way, it is similar to the CWT, but it has an essential difference. Whereas Garbor transform used fixed width window, the CWT employ a progressively larger window given by the wavelet scale (i.e., the large scale corresponds to the low frequency end of spectrum).

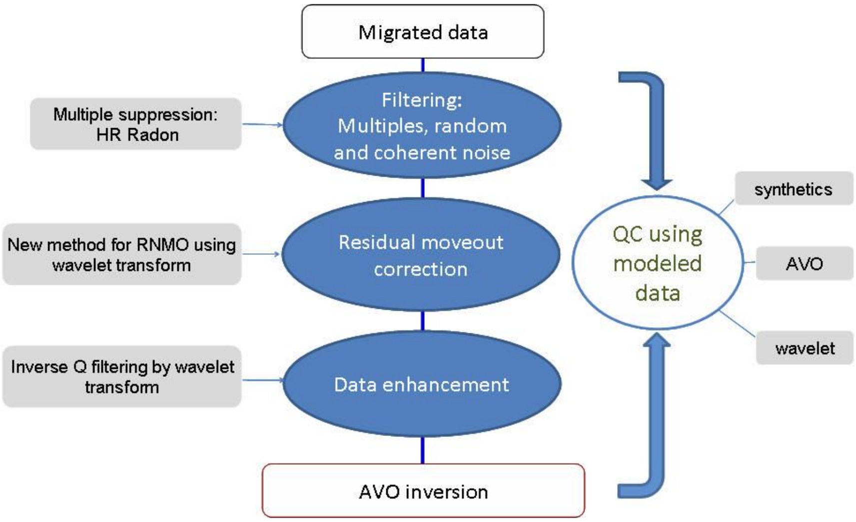

Figure 1 – seismic data preconditioning workflow consisting of three main steps represented in the blue ovals consisting of noise suppression, gather alignment, and band extension. The gray boxes on represent the main employed filtering methods (left) and quality control targets (right).

To develop a series of wavelet domain filters for data enhancement and gather alignment, we closely follow the formulation presented by Wang (2006). Thus consider a plane wave solution to the one-way wave equation propagating with a radial frequency ω , from time 0, at the recorder, up to an arbitrary time τ , can be written as

$$U(\tau,\omega) = U(0,\omega)\Lambda(\tau,\omega)\Theta_1(\tau,\omega), \qquad (1)$$

where Λ and Θ_1 are, respectively, the terms responsible for the amplitude and phase changes along the propagation path, including the effect of absorption and dispersion. Additionally, we may consider small time shifts with respect to τ , which may be accounted for by a phase shift operator $\Theta_2(\Delta\tau,\omega) = \exp(i\omega\Delta\tau)$ to yield

$$U(\tau+\Delta\tau,\omega) = U(\tau,\omega)\Theta_2(\Delta\tau,\omega). \qquad (2)$$

Now let the 1-D CWT in the frequency domain be represented by a scaled version of the inverse Fourier transform, which is given by

$$U(\tau,s) = \frac{\sqrt{s}}{2\pi}\int_{-\infty}^{+\infty} U(\tau,\omega)\,\psi(s\omega)e^{i\omega\tau}d\omega\,, \qquad (3)$$

where s represents the scale of the mother wavelet ψ , corresponding to a central pass band frequency, given by $\omega_c = s\omega$. The goal is to build inverse filters $\Lambda(\tau,\omega_c)$, $\Theta_1(\tau,\omega_c)$ and $\Theta_2(\Delta\tau,\omega_c)$, which can be applied in the wavelet domain to compensate for amplitude and phase due to absorption and dispersion, as well as residual moveout correction, respectively.

The phase is usually handled during conventional processing. Since we work with prestack migrated data, it is reasonable to assume that phase correction has already been applied. According to Wang (2006), a stable inverse Q filter for the amplitude can be given by

$$\Lambda\,(\tau,\omega_c) = \frac{\beta(\tau,\omega_c)+\sigma^2}{\beta^2(\tau,\omega_c)+\sigma^2}, \qquad (4)$$

where σ^2 is a stabilizing factor, which is a small positive number, and

$$\beta(\tau,\omega_c) = \exp\left[-\int_0^{\tau}\left(\frac{\omega_c}{\omega_h}\right)^{-\frac{1}{\pi Q(\tau')}}\frac{\omega_c}{2Q(\tau')}d\tau'\right], \qquad (5)$$

with ω_h representing the highest frequency in the seismic band.

The residual moveout can be handled very naturally in the time-frequency domain by computing the phase differences between a reference trace (e.g., a partial stack of amplitudes) and each trace of the gather. From the phase differences the time shifts can be readily obtained and applied for each time and frequency to yield $U(\tau+\Delta\tau,\omega_c)$.

Application to Real data

The seismic data preconditioning workflow presented in Figure 1 has been applied to a prospect delineation study in a marine environment offshore Brazil. The main target is the oil sandstones associated with the low density intervals observed at the well log (Figure 2, blue). In the area there are a large number of volcanic cones (see e.g., Cainelli and Mohriak, 1998), which condition the geometry and continuity of sandstone bodies. Previously to this study, one exploration well has been drilled in the area (Well A), reaching an oil-filled reservoir. Original amplitude data indicates continuity of the reservoir layer. The objective here is to delineate the oil saturated zone of the sand body. The first task was to improve the quality of the seismic information through the preconditioning workflow. Figure 2 show the result of each step of the workflow in the common reflection point (CRP) gather corresponding to well A. From the original gather, on the far left **(a)**, to the final preconditioned gather **(d)**, both signal-to-noise ratio and vertical resolution have been significantly improved.

Figure 2 also show, on left side of each gather, the density log and a synthetic trace from well A. The density log is distinctively lower in the oil intervals (blue), therefore serving as a direct hydrocarbon indicator. Notice the increased resolution made it possible to see thin layer intercalations within the zone of interest.

The impact of the seismic data preconditioning workflow on the seismic image may be appreciated in Figure 3, showing stacked sections from original data **(a)** and preconditioned data **(b)**, respectively. The whole section displays sharper contrasts, and better thin layer definition and lateral continuity, after preconditioning. This is especially noticeable around and below the volcanic cone in Figure 3.

AVO inversion

The preconditioned gathers are inverted to recover AVO reflectivities Rp, Rs, Rd, respectively for *P-* and *S-wave* impedances, and density, using an Aki & Richards type approximation. The goal is to also obtain reliable estimates of the density, considering that it is a hydrocarbon indicator for this prospect. To make density estimates more stable, we impose a linear correlation between VP and density, which has been verified to hold at the well.

AVO reflectivities are then separately inverted to yield their corresponding layer elastic property variations, generally represented by ΔI_{HS}. To do that, we apply the method developed by Oliveira et al. (2009) based on an exact zero offset reflectivity formulation in the frequency domain. This inversion is carried out completely independent from the low frequency information that is absent from the seismic data, thus providing only the high frequency elastic property contrasts of each layer with respect to a smooth background. The main idea is to extract the maximum amount of the information contained in the seismic data, and then merge that with the stratigraphic background model described in the next section.

Stratigraphic background model

An ideal background model is required to honor the stratigraphic and structural frameworks of the area, without introducing information beyond the lower limit of the seismic bandwidth. Figure 4 show the interval velocity derived using conventional methods, well and seismic information, with a splice of the high-resolution velocity section derived using the horizon cube (de Groot et al, 2010). This figure illustrates the how interpolation of well derived properties using the horizon cube technology can capture the details of the stratigraphy. A filtered version of that on [0-10 Hz] interval is used as the low frequency model.

Our AVO inversion algorithm gives only high-resolution variations of selected elastic parameters, which we generically represent by ΔI_{HS} (i.e., P- and S-wave impedances and density).

Now let I represent the total value of the elastic parameter, which must combine the estimated elastic parameter variations with the corresponding background model. To obtain I, we use

$$I = \alpha\, \Delta I_{HS} + I_{\text{back}}\,, \qquad (6)$$

where I_{back} is the low frequency (background) model generated with the horizon cube and well-log data, and α is a scaling factor between the high frequency component of both well logs and estimated elastic attribute variations.

A Bayesian probability based approach for DHI using elastic attributes computed using equation (6), has been validated to produce reliable DHI for the area, by showing close agreement with well-log data and drilling information. To highlight areas with high probability for oil accumulation, we set an indicator variable $\delta = 1$, if $Po \geq Pc$, where Po and Pc are respectively oil probability and a cut-off value selected from well information, and $\delta = 0$, otherwise. Figure 5 shows a comparison of the original amplitude data **(a)** with our probability based indicator **(b)** over a horizon slice corresponding to top sand. Note, in **(a)**, the large area of initial target anomaly, reflecting spatial continuity of low impedance sand, as represented by the hot colors. On the other hand, oil indicator image reveals favorable areas for the oil sands. The difference between the original amplitude anomaly and the oil indicators probably defines the water saturated sands.

Conclusions

This work has demonstrated that is still room for systematically improving conventional AVO based studies by special methods applied both before and after the inversion procedure itself. Multispectral analysis provides ideal framework for seismic data preconditioning, whereas automatic interpretation tools such as the horizon cube gives unique chance to incorporate realistic stratigraphic and structural information into the final elastic parameter model without introducing any bias in the inversion routine.

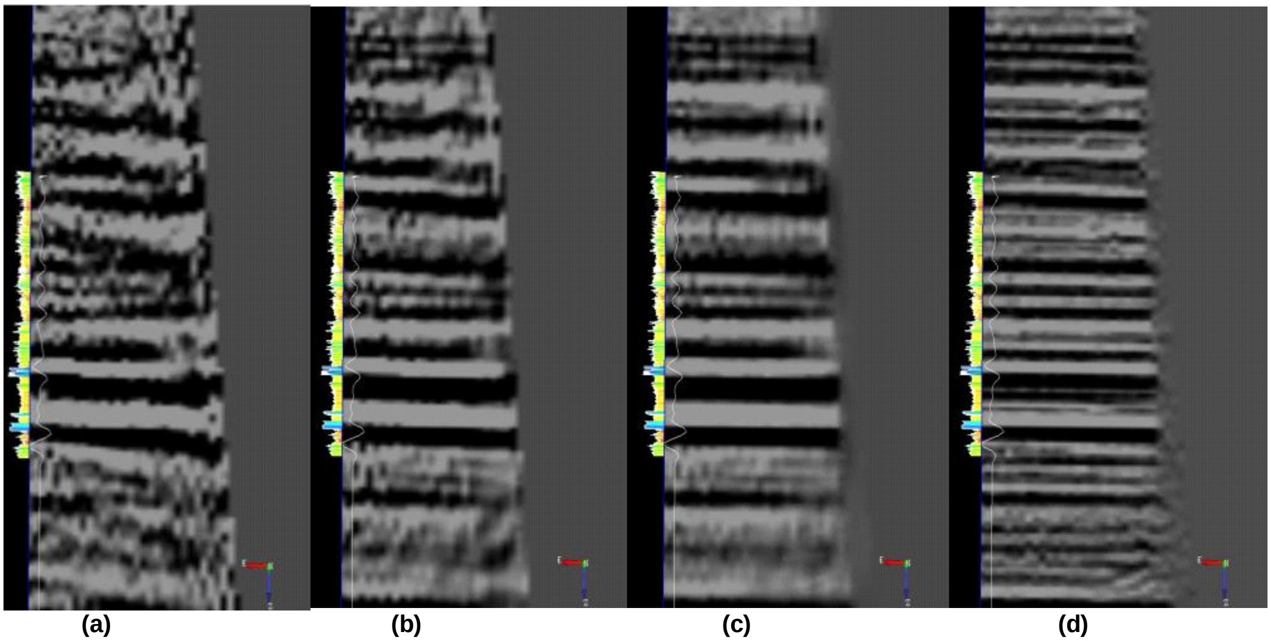

Figure 2 – CRP gather corresponding to well A at different stages of the seismic data preconditioning workflow. **(a)** original gather; **(b)** after residual multiple suppression; **(c)** after gather alignment; **(d)** after inverse Q filtering. Displayed on the left side of each gather are a color filled image of the density log and a synthetic seismic trace. Note how signal-to-noise ratio, vertical resolution and well tie have been significantly improved.

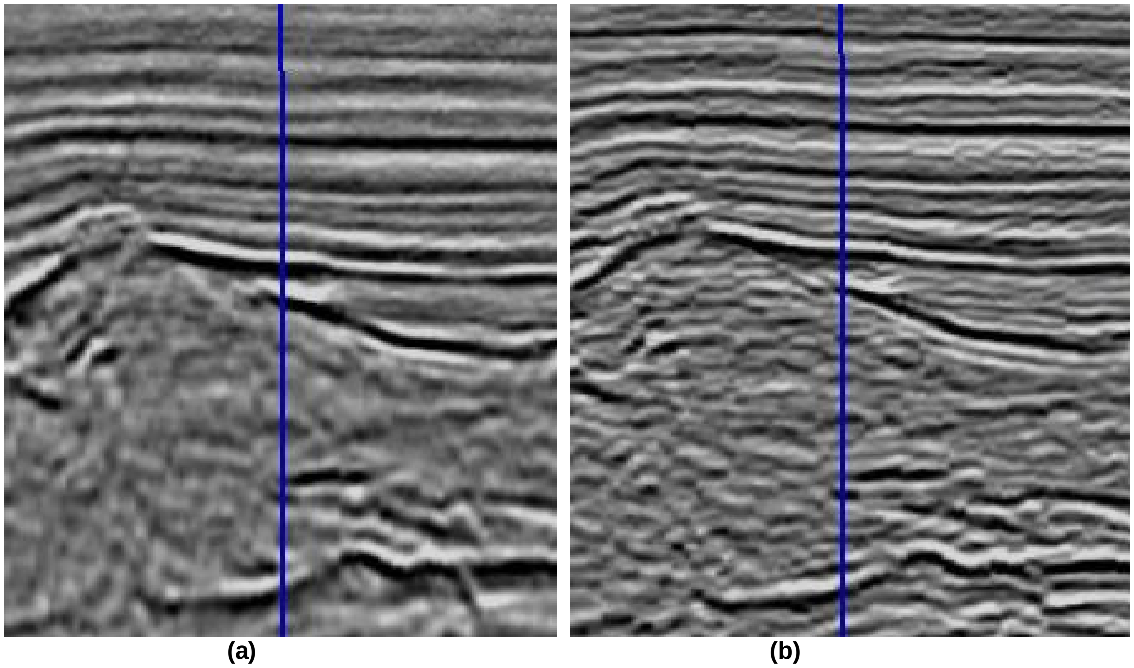

Figure 3 – Stacked sections of the prospect showing the volcanic cone and the low impedance sandstone is showing lateral continuity of well A. The impact of the seismic data preconditioning workflow is clearly noticed by comparing the sections before **(a)** and after **(b)** application of the workflow.

Acknowledgments

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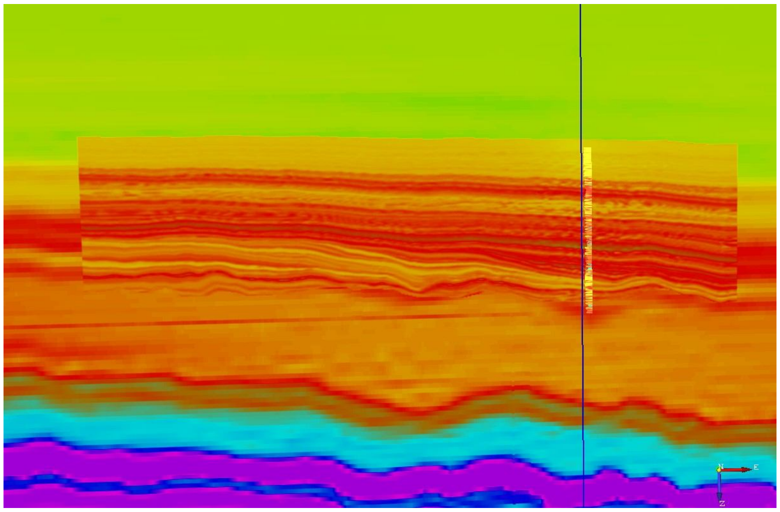
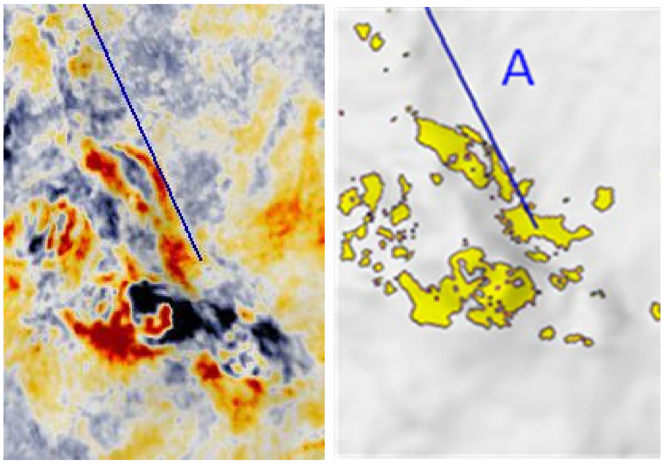


Figure 4 – Interval velocity derived using conventional method for integrating seismic and well information, with a spliced portion of the interval velocity model derived with the horizon cube technology. Also displayed in the figure is the velocity log from Well A.



(a) (b)

Figure 5 – Horizon slices over the top sandstone reservoir showing selected target anomalies from original stacked amplitude volume **(a)** and the probabilistic oil indicator volume **(b)**.