Customization of Preconditioning and Inversion Workflows for Broadband Data. A Case Study from the Campos Basin, Brazil.

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Abstract

Each year an increasing number of broadband seismic surveys are acquired over the Brazilian hydrocarbon basins. Being rich both in low and high frequency content, broadband data promises to decrease uncertainty in reservoir characterization and improve vertical resolution. A detailed analysis of some critical reservoir characterization steps is showcased here using broadband seismic data acquired by CGG in the area of Campos Basin between January and June 2014. They illustrate specific strategies to get the most benefit from broadband data and the uplift brought when this type of data is integrated into reservoir characterization workflow.

Introduction

The whole acquisition covers an area of approximately 10,000 square kilometers. The test was performed on an area of interest extending over 100 square kilometers and encompassing 3 wells. The narrow azimuth data with a variable-depth streamer profile (10 to 50 m) was acquired in super-deep water basin and the analysis was focused on post-salt clastic sediments of Santonian age.

As for any type of seismic data, a fundamental principle is: reservoir characterization will only fully benefit from the seismic data, if it is properly processed and all parameters are established in an optimal way, with the objective to recover more signal and attenuate as much noise as possible. While this basic principle is respected, the reservoir characterization of broadband data gives good results. The objective of this work is to illustrate this principle in application to a real seismic dataset.

Three key steps of a reservoir characterization workflow are discussed in this work, to illustrate both the specific challenges and benefits of broadband data:

1- Seismic data preconditioning;
2- Spectral analysis and wavelet estimation;
3- Inversion initial model and parameters optimization.

Seismic data preconditioning

Proper quality control of seismic data is essential during data acquisition and processing. When the seismic data is declared to be ready for reservoir characterization, the final enhancements are taken and this step is called seismic data preconditioning. Quality controls ensure the improvement of seismic data quality during preconditioning. It should be performed using appropriate attributes, defined in function of the final objectives of the project. Focus on the following aspects can be mentioned:

Signal frequency, phase and amplitudes variations (wavelet stationarity);
Lateral consistency of signal and level of noise;
Pre-stack signal;
Interpretation relevance or the link of the seismic data with hard data (logs, etc.) (Araman et al, 2014).

Beyond the direct verification of the signal, two main quality controls approach should ideally be combined:

- Statistical parameters calculated at the survey scale, that represent the global behavior of the signal: signal-to-noise ratio (SNR), Quality and Anomaly attributes for amplitude versus offset (AVO) (Coleou et al., 2013), enhanced bandwidth at every preconditioning step;
- Tools using forward modeling from well log data: well-to-seismic tie, AVO curves comparison between seismic and synthetic, and other procedures which assess whether the data is getting more interpretable, represents the reservoir model and insures that the rock properties can be calculated from amplitude values.

Three preconditioning procedures were performed on the dataset, taking special care of the low frequencies and trying to preserve them as much as possible:

1. Random noise attenuation applied to gathers;
2. Structural filtering applied to angle stacks;
3. Spectral shaping applied to angle stacks.

Random noise attenuation considers the coherent seismic data as signal and the incoherent as noise to be attenuated. The projective filtering is carried out in the f-x domain. For this case study, harsher filter parameters were chosen for the high frequencies compared to the low frequencies. This parametrization concentrates most energy of residuals in the high frequency range. The filter parameters are optimized using residuals analysis, AVO curves analysis before and after the filter application and AVO attributes analysis to insure that they are getting less noisy after filter application but don’t change character.

After preconditioning of gathers, the decision about angle intervals for partial stacks calculation is taken through data evaluation, AVO analysis tests and inversion tests. The angle intervals should include seismic data of sufficient quality and allow recovery of the elastic properties in pre-stack inversion afterward. Angle stacks 6-18 degrees (Near), 16-28 (Mid), 26-38 (Far) and 36-48 (Ultra-Far) were created for this dataset.

Structurally consistent filtering was applied to angle stacks: it filters along the local dips computed on the reference data. This filter decreases the energy of the low frequency component of the data and depends significantly on the reference data choice. This filter increases values of SNR in all angle stacks - Figure 1 shows Signal-to-Noise Ratio for Mid angle stack.

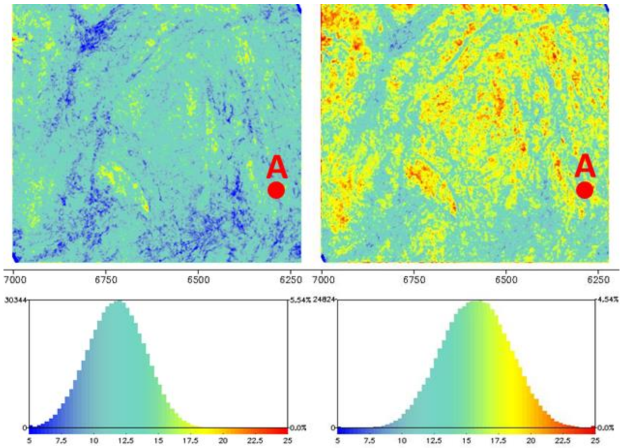

Figure 1. Signal to Noise Ratio estimated in reservoir before (left) and after (right) structurally-consistent filter application for Mid angle stack.

After evaluation of the results, differences in the frequency spectrum of the partial stacks were observed. A spectral shaping applied to angle gathers improved the AVO. Figure 2 contains the spectra estimation for angle stacks before and after spectral shaping.

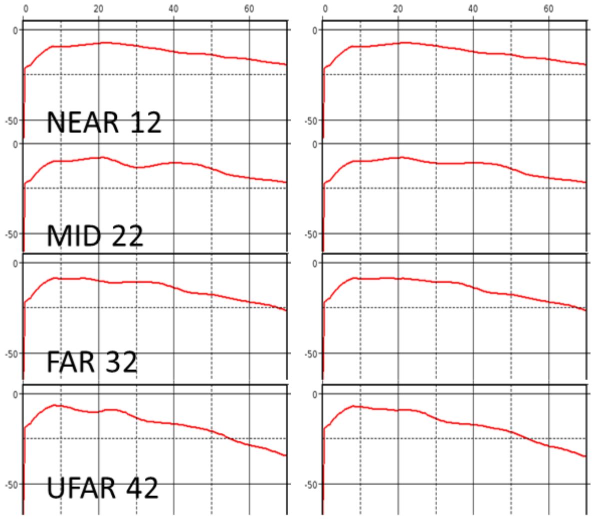

Figure 2. Angle stacks spectra before (left) and after (right) spectral shaping.

Figure 3 shows how the AVO response improved after spectral shaping application – (D to E) - and also the step by step change of AVO at the well location and comparison with synthetic AVO curve (A).

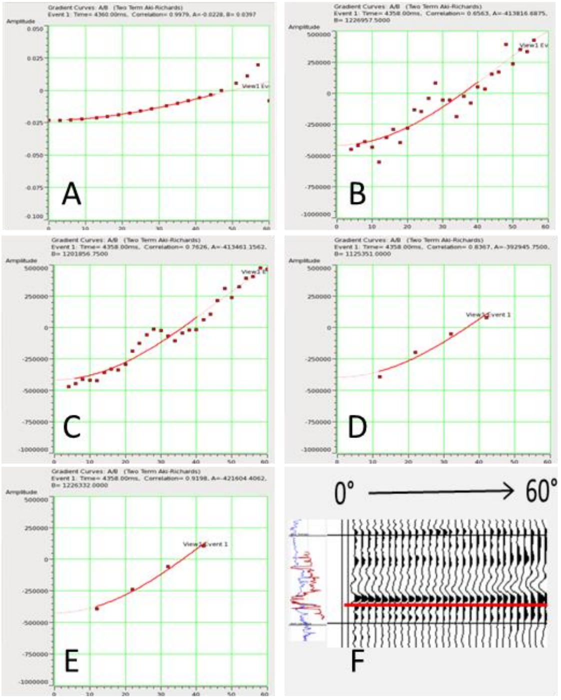

Figure 3. Changes in AVO behavior after each preconditioning step. A-synthetic gather; B-input gather; C – random noise attenuated; D – after structural filter applied to angle stacks; E – after spectral shaping; F – input gather at well location.

Wavelet estimation

Wavelet estimation is a critical step in the reservoir characterization workflow because it creates the bridge between seismic reflections and reflectivity series.

Wavelet extraction for broadband data should be performed taking into account specific challenges related to the presence of low frequencies in the data.

A common approach of wavelet estimation is via a deterministic or Bayesian extraction using well logs through the search of maximum in the cross-correlation function between seismic and synthetic traces. The main challenge for broadband data is the usually short interval of log data information which does not cover two or more wavelet periods, in order to properly estimate ultra-low frequencies. Before the wavelet extraction at well location using well logs, a statistical wavelet is estimated over a wide time window including the reservoir – this estimation uses autocorrelation of seismic traces and shows the full spectra present in the seismic data in the chosen interval. The window should be big enough to cover the first few Hertz in the signal spectrum – a 1000ms window was chosen in this case. This first statistical wavelet is used as initial/priory wavelet for following estimation to bring the low frequency content which cannot be reliably estimated in short interval.

The energy corresponding to different frequency bands inside the test area showed significant lateral variation. Figure 4 contains the map of energy corresponding to the signal of 5 Hz in a time window of 600 ms around the reservoir calculated for the full stack. This lateral variation is confirmed by well wavelet extractions: wavelet extracted in well A showed richer low frequency content than wavelet extracted in well B.

When a multi-well wavelet is extracted using well A and well B (Figure 5), it repeats the shape of the wavelet "richest" in low frequencies, extracted in well A. This is visible on the individual wavelet spectra displayed on Figure 6. For the high frequencies the multi-well wavelet followed the poorest well wavelet. It is an important fact to be considered in the case when we have well data in a weak low frequencies area. The frequency maps analysis before the final wavelet estimation is crucial to avoid missing those low frequencies in the final wavelet.

As shown is previous works, the impact of low frequencies to the inversion result is very significant – both considering amplitude spectra and phase spectra (Yang et al., 2016).

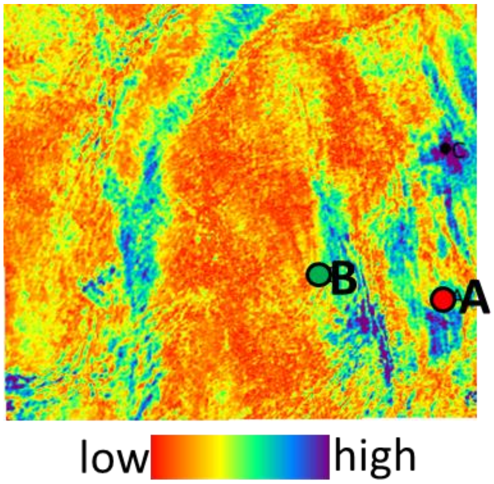

Figure 4. Spectral decomposition result. Map of energy corresponding to the signal of 5 Hz in the full stack.

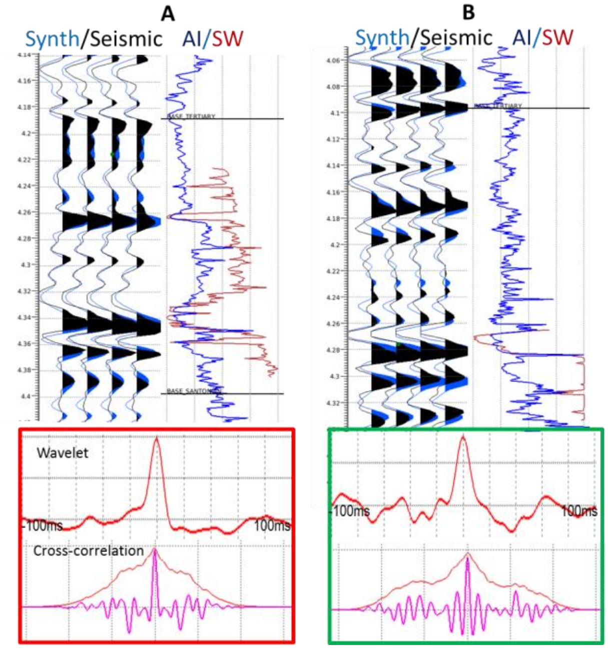

Figure 5. Calibration of well A and B with full seismic stack.

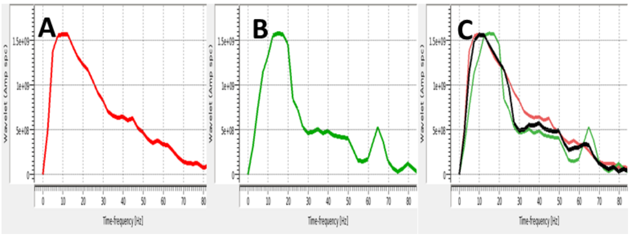

Figure 6. The amplitude spectrum estimated in wells A (A) and B (B) and multi-well amplitude spectrum (C).

In both wells A and B the window of logs presence is too short for reliable extraction of lowest frequencies and this part was stabilized through the use of an a priori wavelet which was statistically extracted in a wide window. The phase of the low frequencies was extrapolated from the mid-frequency part of the spectra (Schakel at al., 2014). Its impact on the inverted results was analyzed during the inversion testing phase.

Inversion

Having a broader bandwidth of seismic frequencies gives certain advantages when performing seismic inversion in order to transform seismic reflections into elastic properties of rocks. In this paper both post-stack (acoustic) and pre-stack (elastic) inversion are performed over the reservoir interval. A low frequency model is required to perform the seismic inversion due to the absence of information corresponding to the first few Hertz in seismic data. For conventional non-broadband seismic datasets, low frequency models are obtained from low-pass filtered impedance logs. If well-logs are sparse and the geology is complex, the well-derived low frequency model may be inaccurate and cause biased inversion results.

This stage of inversion workflow brings significant uncertainty into result because the low frequency model created through log interpolation is conditioned by the number of wells at the area, stratigraphic model reliability and lateral variability of elastic properties. One option to improve the low frequency model is to use seismic velocities. However, while seismic velocities provide information at very low frequencies (0-5 Hz), they are not usually suitable to provide information for the missing frequencies in the range from 5 to 10 Hz with conventional seismic data. Seismic data acquired using variable depth streamers are ideally suited for inversion as they provide directly these missing low frequencies, hence decreasing the dependence on well data to build low frequency initial models.

Figure 7 shows an acoustic inversion plot including seismic stack (A); initial model (B) calculated from seismic velocities and density calculated from a Vp-Rho relationship derived at the well; acoustic inversion result (C). One advantage of inverting broadband data is the decreased frequency gap between seismic velocity and seismic data, which allows the use of the seismic migration velocity field as the initial model for inversion. In the case of sparse spike inversion, as implemented in this example, an additional benefit is the fact that no horizon interpretation is required for model creation.

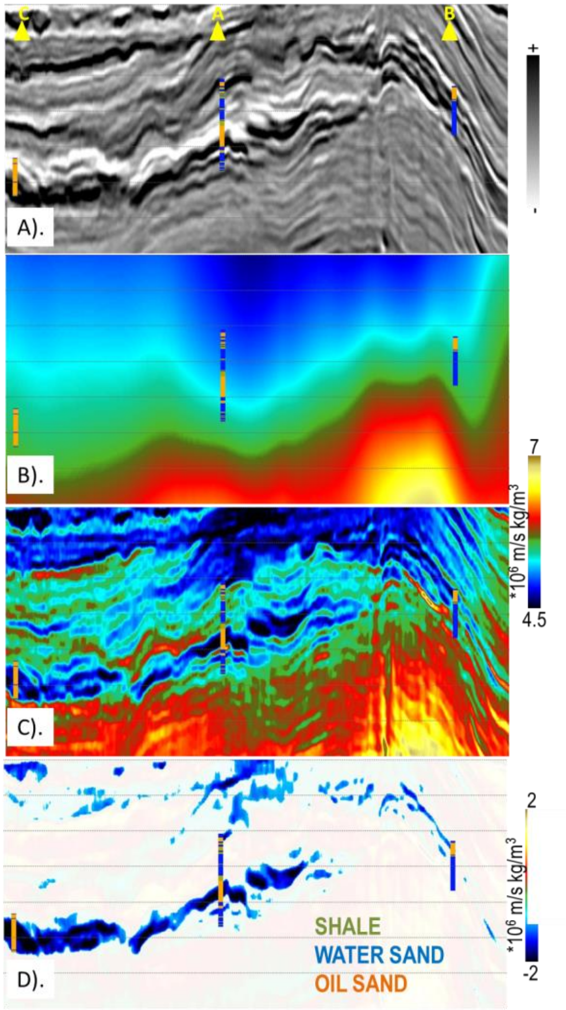

Figure 7. A). Seismic stack. B). Initial model. C). Acoustic Inversion result. D). De-trended Impedance with cut-off applied. Vertical window shown - 350ms.

The reservoir properties values are conditioned a lot by the compaction trend which makes the analysis of absolute values irrelevant. Figure 8 compares the histogram of Acoustic Impedance values in wells (colored by three facies) in absolute values and in relative de-trended values. Compaction trend subtraction allows classifying lithology through the values of de-trended (relative) elastic properties. Figure 7, D shows the de-trended acoustic inversion result with the cut-off applied to separate oil sands (D). This kind of interpretation is demanding for bandpass inversion result quality – the relative impedance values representing seismic bandwidth, and often gives unreliable results when inverting conventional seismic data.

The cut-off application (see Figure 8) shows a good match with 3 wells. Additionally, the pre-stack inversion was performed with Lambda-Rho and Mu-Rho value calculations. Figure 9B shows the Bayesian lithology classification result using Lambda-Rho and Mu-Rho, the color shows the probability of oil sandstone. Comparing to the similar plot extracted from acoustic inversion result in Figure 9A the uncertainty was decreased in facies classification.

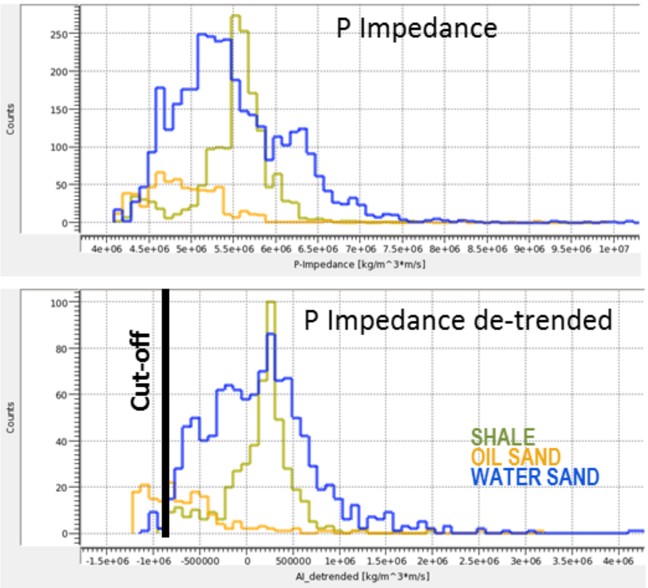

Figure 8. Impact of subtracting the compaction trend to the separation of oil saturated sands in the values of acoustic impedance.

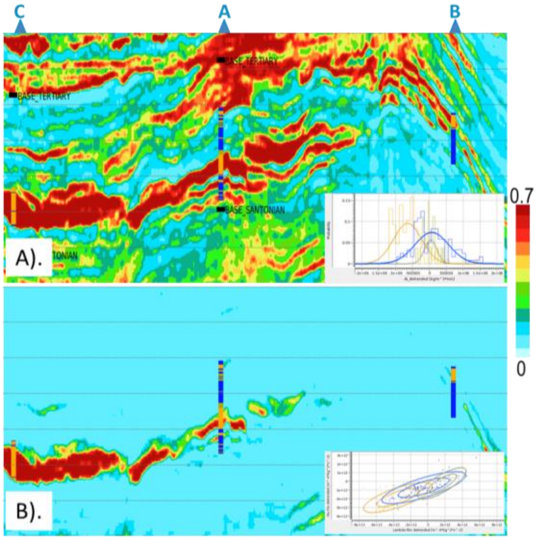

Figure 9. A). Facies classification of acoustic inversion result – probability of oil sandstone. B). Facies classification of elastic inversion result – probability of oil sandstone. Vertical window shown - 350ms.

Conclusions

Broadband data has shown itself to be strategic for reservoir characterization, and its value has been proven in many case studies. In correlation, we have illustrated in this work that while using broadband seismic data relies on the same general principles as conventional data, certain care has to be taken to address its specificities. Quality control during processing ensures amplitude preservation with a focus on low frequencies. Additional data enhancement through the application of preconditioning sequence prepares the seismic data for inversion and can be customized for broadband seismic data. If needed, spectral shaping can be applied to angle stacks.

Wavelet estimation requires special attention to low frequencies, considering the lateral variation of the low frequency signal and the possibly short vertical window where well logs are available. A-priori statistical wavelet can be extracted to stabilize the low frequency part during the following estimation using well logs. Phase can be extrapolated from the mid–frequency part or optimized analysis of the lateral behavior of elastic properties in inversion results.

The deterministic inversion of broadband seismic data can be performed without use of interpolated well properties as initial model. No horizon interpretation is needed to run the inversion. The initial model can be calculated using the migration velocity field with the use of Gardner’s equation for density if the velocity model has reasonable match with wells.

Post-stack inversion showed a very good bandpass inversion result with an excellent match in three available wells. This allowed the interpretation of de-trended inversion result to separate Oil Sands reliably.

Pre-stack inversion showed good match in one available well with Vp and Vs values. Derived Lambda-Rho and Mu-Rho volumes decrease the uncertainty in Oil Sand prediction compared to the acoustic inversion case.

Careful use of broadband seismic data together with current reservoir characterization and preconditioning techniques allow the recovery of the additional value brought by the extended bandwidth of seismic data and obtain an uplift in reservoir model quality compared to conventional seismic within a shorter timeframe due to lower uncertainty in well-to-seismic tie, and the possibility to create a low frequency model from seismic velocities without performing well data interpolation.

Acknowledgments

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