First 4D broadband using multicomponent streamers acquisitions for deep water reservoir monitoring: benefits and lessons learned

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Summary

During the last decades, broadband seismic surveys became more prevalent and for several years this has also been used for time-lapse seismic monitoring of hydrocarbon producing fields or CO2 storage targets.
With optimized survey design and dedicated processing sequences, both the monitor acquisition repeatability and the frequency bandwidth of the useful seismic signal at target level are improved. Since the low frequency part of the seismic signal has a direct impact on the reliability of seismic amplitude inversion, this has led to improving relevant 4D resolution which is crucial during 4D interpretation and integration. In our context of oil field monitoring, we compare base and monitor seismic from standard good quality bandwidth to broadband data. We decoupled the Signal-Noise component of the data from the seismic frequency bandwidth. This permits a more robust estimation of our different 4D attributes. In addition, geostatistical tools have been used to better quantitatively compare conventional and broadband monitor pairs.
The final 4D interpretation and integration step takes benefit of the useful bandwidth from the broadband data thereby allowing for easier 4D attribute handling, the possibility to consider lower values of relevant 4D attributes and the computation of a more representative 4D geobody volumes in the allocation matching process. Also, the geobody interpretation on different monitor pairs can help to better precise the effective fluid and pressure pathways due to field production mechanisms.

Introduction

4D seismic is regularly used for reservoir monitoring over a wide range of reservoir settings and configurations. It is based on the use of at least two datasets acquired at different times of the reservoir life cycle to extract useful information related to production-induced changes.
Broadband data for 3D seismic reservoir characterization has demonstrated the ability to fill the low frequency gap for providing a continue and consistent spectrum over an extended signal bandwidth (Reiser et al., 2012; Mesdag 2015) . Also, the representative wavelet of such data must be well defined among the expanded bandwidth in order to preserve the maximum of lithology resolution (Reiser, 2012; Zabihi Naeini, 2016).
4D broadband surveys are recent and benefit from the increase of navigation accuracy such as source and receiver position repeatability and deep towed multi-component cables control.
From a wide range of reservoirs, the resultant 4D seismic signal due to the production can be challenging to extract, especially while considering thin reservoir layers with limited saturation changes and pressure effects on the matrix, with time-shifts less than 1 or 2 ms (MacBeth 2018). In such a case, broadband dataset will be devoted to providing the maximum of resolution.
Repeated deep-towed multisensor streamer acquisitions offer an effective platform for acquiring 4D broadband data. Deeper tow depths deliver useful low frequencies with an improved signal-to-noise ratio and multisensor recording systems provide repeatable high frequencies unaffected by the variable sea state.

Basics and methodology

The starting point is the very well-known Nyquist theorem: at least two samples (or one sample and the derivatives) per time period or spatial wavelength are needed to correctly describe a continuous phenomenon (seismic wavefield) by a regular version of it. The vertical resolving power of a seismic signal can be described by the information theory (Rappin 2009). The concept of ‘vertical logon' and Shannon's theorem provide the number **N**, of separable points along a seismic signal as the product **N = B.T** (where **B** is the bandwidth of the seismic data and **T** the duration of the record). This limitation can be overcome by enlarging the bandwidth and by using a wavelet-based inversion scheme. In 4D studies, the seismic of the baseline can be considered as a reference model and the monitor as a perturbation of it. The difference of both images using inter-correlation provides time-shifts. The minimum reliable time-shift we can observe depends on the global 4D noise level, the effective frequency bandwidth of the seismic signal (**Be**) and the signal to noise ratio. All these quantities can be estimated from the data. The Woodward's formula can be applied to evaluate the time-shift reliability threshold (Lurton 2002) and is defined as the standard deviation:

$$\sigma_{Tshift} = H\ n/s\ /\ 2\pi B_e$$

where H is a scaling experimental parameter; n/s: noise to signal ratio.

Owing to the recent acquisition survey improvement, the noise level has decreased. At the final stage , the lowest noise level and the broadest spectrum allow to increase the 4D signal resolution. For this reason, we assessed the bandwidth impact according to different type of surveys (conventional and broadband) as well as the band-limited version of the broadband data set with the aim to decouple the contribution of the noise reduction and the bandwidth enlargement.

For preserving the advantage of broadband recording systems, some key data processing steps have been reviewed in order to optimize the 4D repeatability of the broadened signals (Lecerf 2018): De-signature, statics, matching and denoise. Careful attention to de-bubbling and shot-by-shot designature process are key for improving the low frequency signal repeatability. A residual designature filter is generated for each source using the near field hydrophones.

Sail-lines consistent shot-by-shot statics, water column corrections and 4D statics are crucial to enhance the repeatability of high frequencies. Finally, a 4D residual time-shift correction is applied to readjust kinematically, in a 4D sense, both datasets base and monitor. It is essential that any undesirable 3D and 4D time-shifts, due to environmental changes and/or acquisition variations, are corrected before the full wavefield regularization.

In addition to conventional global matching procedure, a specific matching procedure was designed for cross-equalizing the baseline and monitor signal spectra. Signal-only matching operators were designed using a frequency adaptive time window. A specific 4D denoise based on the optimization of the 4D pseudo impedance trace finalizes the 4D broadband post-processing.

Once the seismic signal is preserved as much as possible, the benefits of the broadband must be quantified. At the final post-processing stage, 4D attributes are computed and interpreted for reservoir model update and volume allocation. The quality of the 4D attributes will be analyzed using some statistical metrics and the capability of broadband case to detect useful information at a finer scale will be assessed. The improve resolution should help to better understand the production reservoir behavior.

Field example

We used two 4D seismic campaigns, a conventional-on-conventional acquisition 4D surveys (single hydrophone streamers) and a broadband-on-broadband acquisition 4D surveys (dual-sensors streamers), acquired on a field with more than a decade of oil production. Both 4D surveys were acquired in the course of the on-going production. Importantly, the two base-monitor surveys cover different time periods: conventional base-monitor seismic acquisition -2 years) and the broadband acquisitions -5 years). However, both campaigns started in the same year, so some overlap exists in time which gives the possibility to run a qualitative comparison. Such a comparison could be especially valid in the areas where the production effects are known to last exclusively during the shortest, conventional seismic campaign period. Despite these drawbacks, we have obtained some interesting field-wide observations. The spectra analyses show very different shape between the conventional and broadband data, and a 1 octave broader spectrum at the objective level.

Figure 1 shows the benefit in term of resolution of the 4D signal. The 4D seismic difference from the multisensor acquisitions is displayed at the final processing stage with the warping applied.

During the 4D processing workflow, 4D inversion has been performed using an estimated wavelet. We compared the result of the usual inversion using wavelet estimation with the dual inversion of timeshifts and amplitude on both a band-limited version and the full band of the broadband data set (figure 2). By removing 4D signal secondary lobes, this example clearly shows the benefit of the broadband to yield a more geological-coherent result that can be directly interpreted as physical production phenomenon in the reservoir.

Figure 3 shows the water displacement from an injector moving towards a future producer (arrow 1). Broadband 4D shows a particularly bright positive $\Delta V/V$ signal over a clean background with a very low noise level in comparison with the conventional $\Delta V/V$ image. Even close to the location of the injector's trajectory where the water must have quickly arrived the broadband image shows the water clearer. This shows a high water sweeping detectability level given that the actual continuous production of water by the producer started just almost two years later.

Another interesting feature well seen on broadband data and practically absent from the conventional seismic is a negative $\Delta V/V$ signal at the injector (below Water-Oil-Contact - WOC) related to pressure rise (arrow 2).

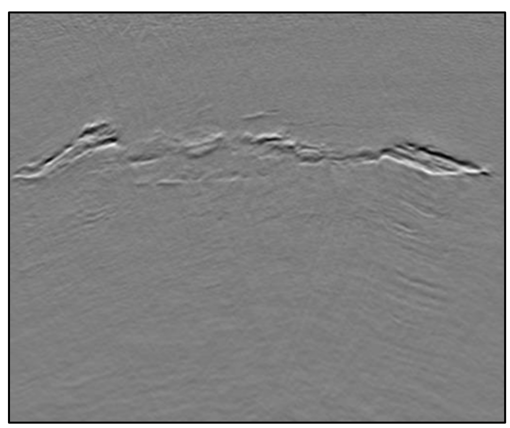

Figure 1: 4D broadband difference wraped

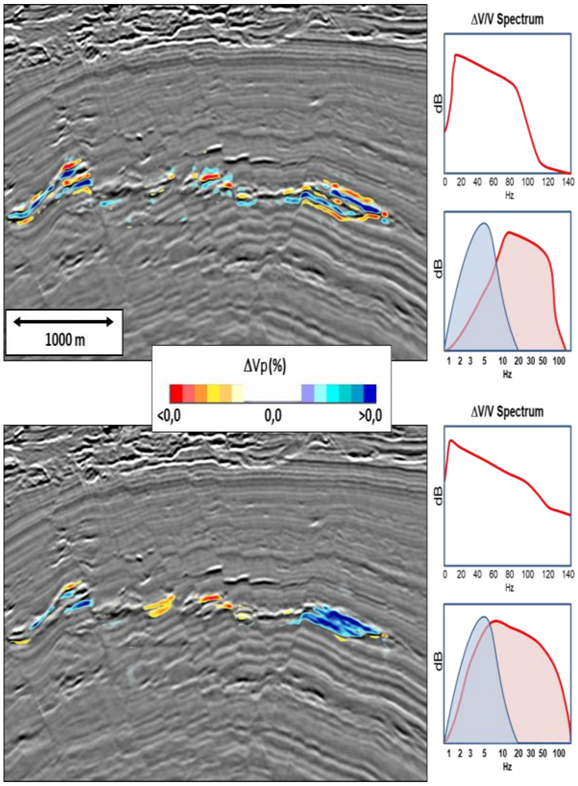

Figure 2: 4D attribute estimation using band-limited (top) and broadband (bottom) data set. Top: Spectrum in linear X scale corresponding of ΔV/V computed from the amplitude changes. Bottom: Spectrum in log X scale corresponding of the ΔV/V computed from amplitude change in red and ΔV/V derived from dynamic warping in blue.

A rise of the Oil Water Contact (OWC) is better seen on the broadband data than on the conventional seismic (arrow 3) given that this rise has already happened at the time of the conventional seismic monitor.

It exists a stronger positive ΔV/V signal at the WOC on broadband data when compared to the conventional data.

In addition to this interpretation step, we can define more precisely the most realistic threshold between noise and signal of the 4D attribute. The geobody computation can be launched with more confidence in order to evaluate the rock volume involved by production effects.

To compare a bit more quantitatively, we used geostatistical analysis on both conventional and broadband volume, especially to evaluate the lateral statistical behaviour of the 4D attributes. The figure 4 shows the variogram for both data sets on which we clearly see the larger dynamic of the 4D signal for the broadband case. From the variogram description (Figure 4), we also applied some a posteriori filtering in order to build a more global water swept volume, including attribute computed on both types of dataset and showing better the water pathways from the injector towards the producer.

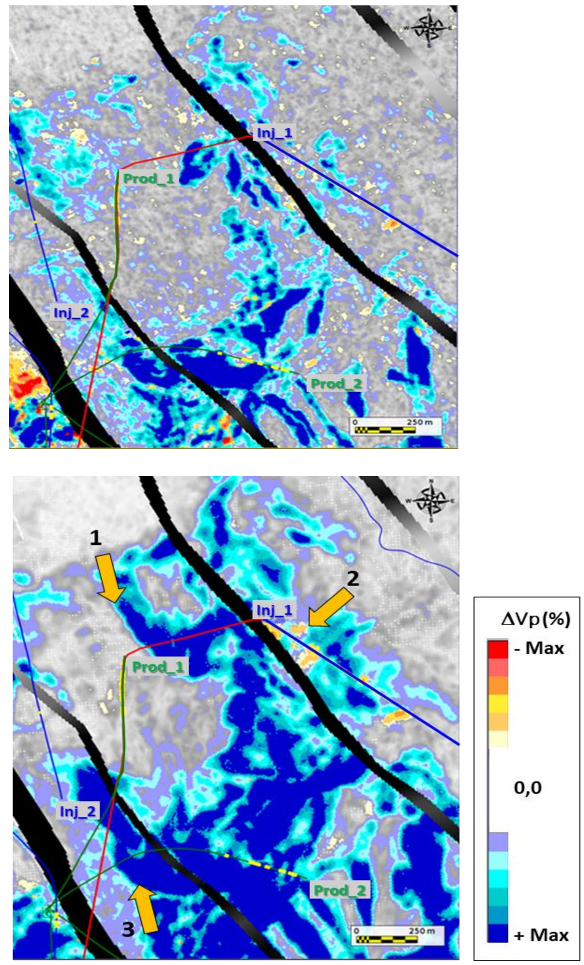

Figure 3 Map a 4D velocity change attribute from standard 4D (left) and broadband data set (right).

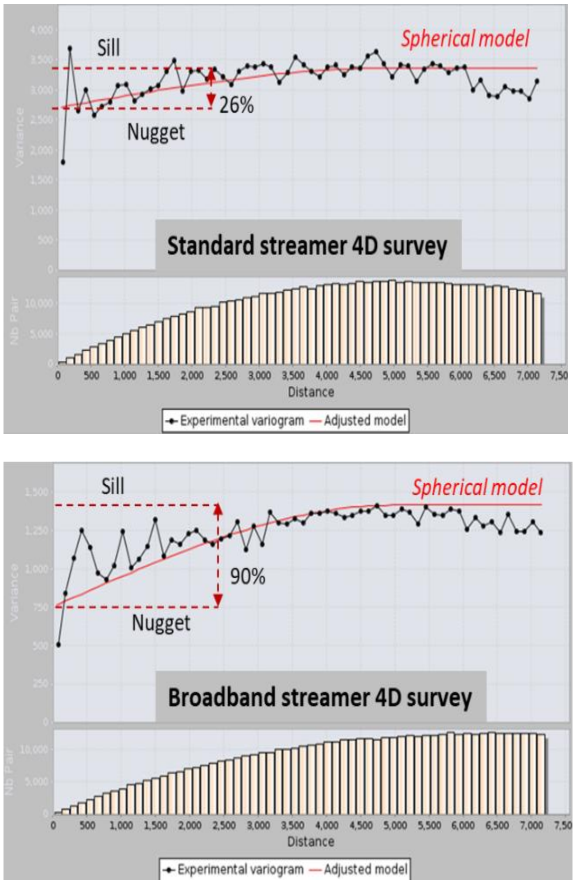

Figure 4: Statistical analysis of 4D maps. The broadband case (right) shows much higher dynamic.

Conclusion

The success of any 4D project depends upon a few factors, including optimum 4D seismic acquisition, the seismic frequency bandwidth at the reservoir level, and being able to deliver the 4D analysis or results in a very rapid and efficient manner. The dedicated processing sequence delivered an optimum seismic product for the quantitative interpretation. Broadening the 4D signal is principally beneficial for improving the resolution of 4D attributes linked to reservoir production effects.

The benefits of the broadband seismic signal are shown by the better delineation of the limit of 4D effects evaluation and the detection of weak signal related to different production mechanisms. In addition, we proposed to use some statistical tools to better characterize conventional and broadband 4D attributes and include both data type in an integrated interpretation scheme.

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