Processing for repeatability and 4D analysis for cross-spread OBC and streamer data in the Campos basin

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Abstract

Time-lapse analysis between streamer and OBC datasets can be challenging. At an early stage in the production of a field, however, such analysis can be the only possibility. We show an example from a field in the Campos basin offshore Brazil, where we performed a time-lapse study utilizing cross-spread OBC and narrow-azimuth streamer data. By carefully addressing the 4D noise during pre-processing and postponing the co-selection to the migrated domain using common-offset-vector binning, a meaningful qualitative 4D signal is obtained. The signal is comparable to what can be obtained from traditional time-lapse analysis of conventional streamer data. The overall normalized-root-mean-square reached 0.15. This level of repeatability is considered high for a 4D analysis using cross-spread OBC and narrow-azimuth streamer data.

Figure 1 – *Map showing the location of a field in the Campos basin offshore Brazil.*

Introduction

Marine seismic exploration for hydrocarbons is typically done with streamer acquisition. When a discovery is made and production of the field has started, time-lapse monitoring of the subsurface becomes necessary in order to try to optimize the production strategy. Production-related infrastructure often creates blind zones in terms of subsurface illumination. Streamer acquisition can to a certain extent handle such blind zones using undershoots. However, because desired follow-up monitoring needs repeatable acquisition geometry, ocean-bottom seismic data acquisition is generally preferred. Therefore, early on in the production cycle, there is often both streamer as well as ocean-bottom seismic data available. That means that at this early stage, there is often an opportunity to get an early estimate of time-lapse subsurface variations due to the production of hydrocarbons, from the combination of streamer and ocean-bottom seismic data.

The difference between the acquisition geometries of ocean-bottom and streamer seismic acquisition often result in rather different illumination patterns. Such differences hamper any desired time-lapse analysis. Several solutions were proposed to reduce these limitations. One such strategy focuses on co-selection in the pre-migration domain (Haacke *et al.,* 2013). However, in some cases, the offset-azimuth distributions for both

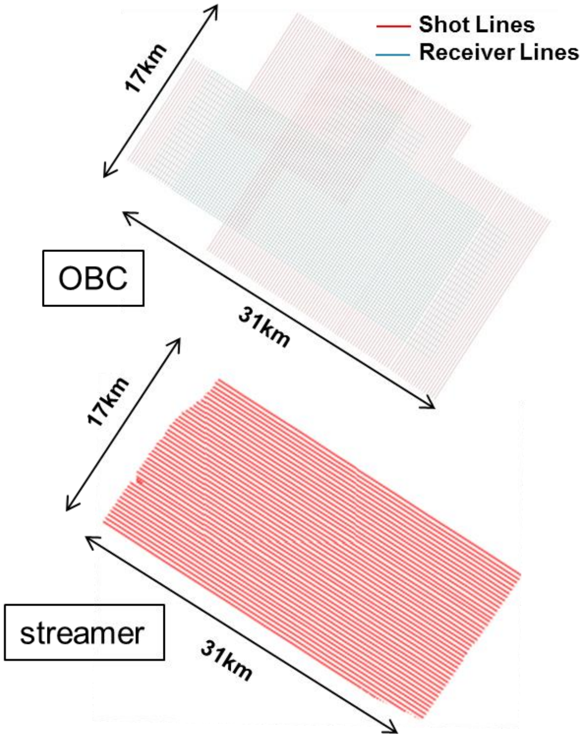

Figure 2 - *Survey acquisition geometries for both the OBC and streamer cases.*

surveys are too different to allow such co-selection. Other strategies focus on the post-migration domain with amplitude matching in the angle domain (Theriot *et al.,* 2015) or compensation of spectral differences between OBS and streamer (Wei *et al.,* 2016). Least-squares migration (e.g, Tarantola, 1987 and Wang et al., 2016) in principle promises to remove the imprint of the acquisition geometry on the image, and as such is expected to have a future impact on the time-lapse studies using data obtained from differing acquisition geometries.

Between 2010 and 2013 a cross-spread OBC data set covering 512 km² was acquired offshore Brazil over a hydrocarbon reservoir located in Campos basin (see Figure 1), in an area with varying water depth (from 150 - 1700m). The cross-spread geometry provides data with a wide azimuth distribution containing offsets up to 13km (see Figure 2). In 2005 a conventional towed-streamer dataset was acquired over the same area. This streamer survey has a narrow-azimuth distribution with maximum offsets up to 6600m only, making 4D analysis challenging. These two datasets, however, provide an opportunity to monitor this area for any subsurface variations due to production between 2005 and 2013. In order to mitigate the large difference in acquisition geometry, we follow largely the approach suggested by Lecerf *et. al* (2010), i.e. we postpone the co-selection to the post-migration stage. This is facilitated by offset-vector binning the OBC data which are migrated individually. In this way some offset and azimuth information is preserved into the post-migrated domain. A co-selection based on the pre-stack offset-azimuth distribution from the streamer data then allows a co-selection in the migrated domain. Furthermore, the preservation of the azimuthal information in the migrated domain allows for further 4D de-noising in the azimuthal direction (such as azimuthal statics and residual de-multiple) prior to co-selection. During pre-processing of the OBC data we focus on removing 4D noise related to node positioning, water-column variations, receiver ghost and free-surface multiples. To provide a fair comparison with the streamer data, we make sure to apply receiver-side ghost-wave elimination to the streamer data using a bootstrap approach in the τ-p domain (Wang *et al.,* 2013). This enables us to reduce spectral differences between the two datasets and maintain a broadband spectrum in the global matching process.

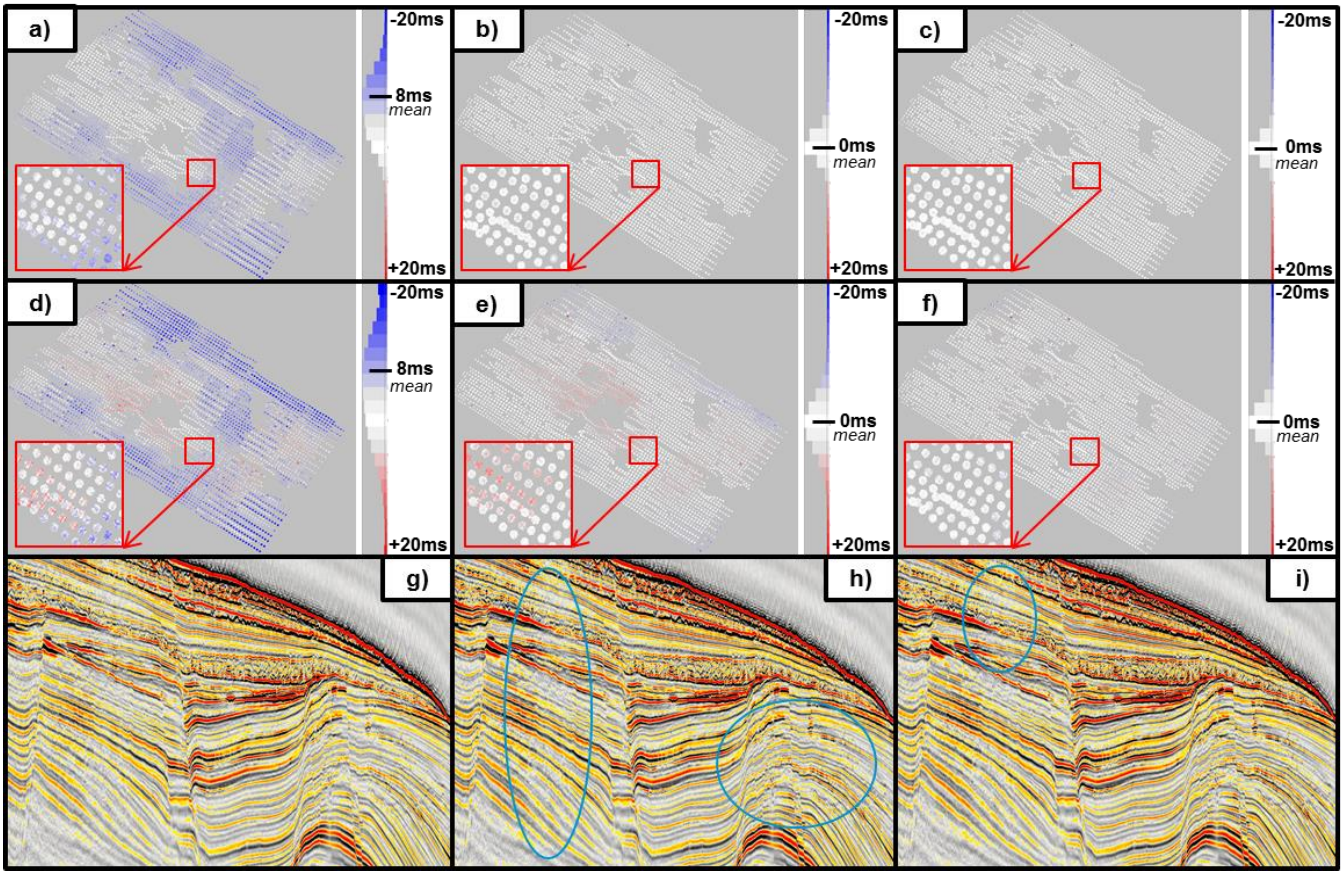

Figure 3 - *Misfit of travel-time of the direct arrival (a) and water-bottom multiple (d) for each shot-receiver pair before statics application; misfit of travel-time of direct arrival (b) and water-bottom multiple (e) after statics application obtained from inversion using the direct arrival only; misfit of travel-time of direct arrival (c) and water bottom multiple (f) after statics application obtained using joint inversion of the direct arrival and water-bottom multiple travel-time; migrated down-going stacked section before (g) and after (h) statics application using the statics derived from the direct arrival travel-time inversion only, showing an improved stack response; migrated down-going stacked section after statics application using the statics derived from the joint inversion of both the direct arrival and water-bottom multiple travel-times (i).*

Pre-migration processing for repeatability

Uncertainties in positioning as well as water column statics are known sources of 4D noise. Amini *et al.* (2016) show how the receiver positioning and water velocity variations can be jointly inverted from the direct arrival times recorded in the ocean-bottom data. Figure 3a shows the difference between the measured and calculated travel-time of the direct arrival before inversion for each receiver position, while Figure 3b shows the same after inversion. We observe that the updated receiver position and water velocity result in a smaller misfit between the calculated and measured direct arrival travel-time, as expected. At the same time, we can also look at the first-order multiple of the water-bottom (WB) and calculate the difference between its measured and calculated travel-time. Because this multiple travels a longer distance in the water than does the direct arrival, it provides extra sensitivity to the water-velocity variations. When plotting the resulting misfit from the WB multiple, we observe that even though the direct arrival misfits are small and near zero (cf. Figure 3b), the overall misfit for the WB multiple is still somewhat larger (cf. Figure 3e). We can use this extra sensitivity of the WB multiple to our advantage by including it as an extra constraint in the inversion. When doing this, we see that the misfits for the WB can be further reduced (cf. Figure 3f) while also still further reduces the overall misfit level for the direct arrival travel-time (cf. Figure 3c, in particular the more peaked distribution of the misfits around 0ms, as evidenced by the histograms). Figures 3g – 3i show how the stack response benefits from the updated receiver positioning and the water velocity, and the resulting static corrections.

It is known that the down-going wavefield is preferably used for 4D comparison with streamer data, as it provides a more similar illumination to the streamer data, than does the up-going wavefield (e.g. Lecerf *et al.*, 2010). Because the water-depth is varying substantially across the survey, the calibration of the geophone used in the PZ summation to achieve the up-down separation, is more challenging. A 3D calibration operator has been computed for each sensor using the cross-ghosting methodology (Hugonnet *et al.,* 2011), leading to a high correlation (on average above 0.9) between the cross-ghosted hydrophone and cross-ghosted calibrated geophone. This allowed for a good quality separation of the up- and down-going wavefields.

Free-surface multiples are known sources of 4D noise. It is important to apply surface-related multiple elimination (SRME) prior to do any 4D signal analysis. It is known that SRME for cross-spread OBC data is challenged by the acquisition geometry. To overcome this, instead of using SRME, a modeling approach can be used to predict the multiples using a reflectivity model based on an image (e.g. Pica *et al.,* 2006). In this method, we use the down-going wavefield in a mirror migration procedure (e.g. Clarke *et al.* 2006) to obtain an image, as this provides a better shallow image than using the up-going wavefield. This helps to improve the accuracy of the predicted multiples that are then subsequently adaptively subtracted. Figure 4 shows the resulting down-going migrated stacked section before and after removing the multiples in this way, indicating a good quality free-surface multiple removal.

Post-migration processing for repeatability

Both the streamer and OBC data were migrated using VTI Kirchhoff pre-stack depth migration using the same velocity model. For the OBC data, the down-going wavefield was migrated using mirror migration (e.g. Clarke *et al.* 2006). Common-offset-vector (COV) binning of the OBC data allows the preservation of azimuthal and offset information beyond migration, because each COV volume will have an associated average azimuth and offset value. Together with the pre-stack offset-azimuth information from the streamer data, this information can be used to perform a co-selection in the migrated domain. Before doing such co-selection, slight azimuthal effects observed on so-called SNAIL gathers (gathers sorted in increasing azimuth within each offset range), and not present in streamer gathers, were corrected using an azimuthal statics correction. We further eliminated any remaining 4D noise using residual demultiple, residual moveout correction as well as some residual denoising. The residual demultiple benefited from the preserved azimuthal information.

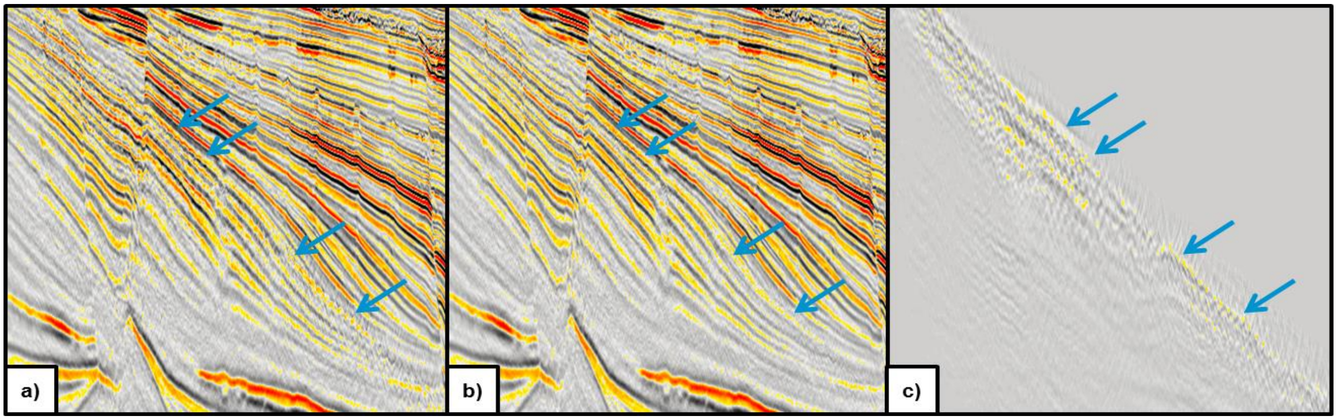

Figure 4 - *Stacked down-going migrated inline section (a) before and (b) after application of SRME and (c) the difference.*

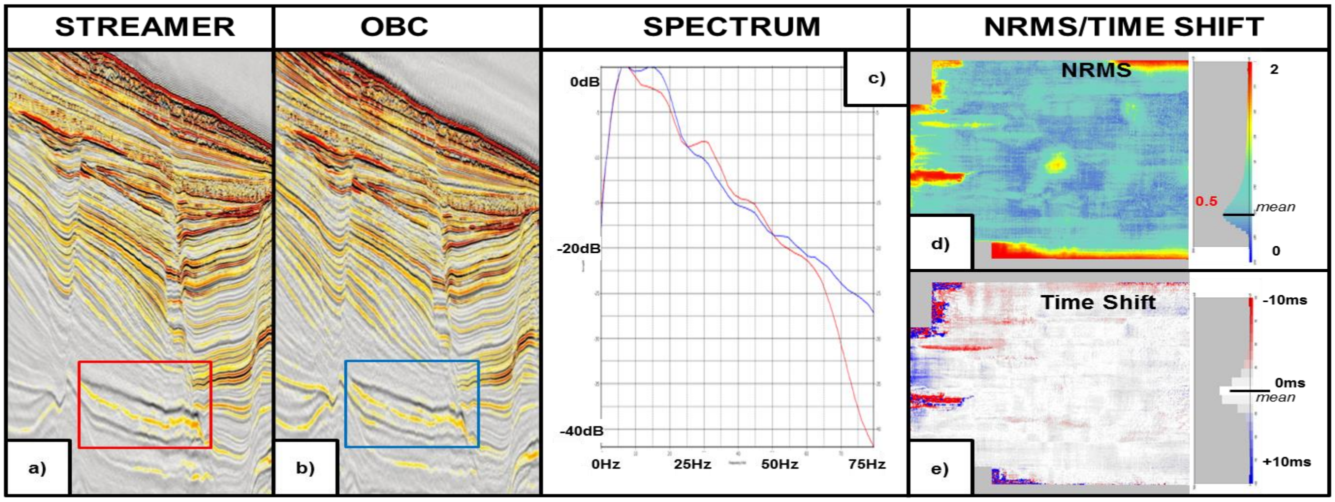

Figure 5 - *Displays are before global matching application (Input for 4D co-processing). Streamer migrated section (a). OBC migrated section (b). Amplitude spectrum at target level for streamer/OBC (c). Initial NRMS (d) and initial 4D time shift QC map (e).*

Figure 5 shows a comparison in the migrated domain between OBC and streamer data. The streamer data had receiver-side ghost-wave elimination applied in the tau-p domain (Wang *et al.,* 2013). As a result it is clear that the spectra of the stacked sections at the target level appear very comparable (see Figure 5c). Furthermore, just comparing the migrated stacked sections in Figures 5b (OBC) and 5a (streamer), the stacked sections looks very comparable at this stage. When estimating the initial level of repeatability we observe that the NRMS level is about 0.5 with time-shifts nicely centered around 0ms with a small standard deviation. This level of repeatability is considered good considering the large differences between the acquisition geometries of both datasets. We stress that at this stage of the comparison no global matching or 4D co-denoising was applied.

4D signal estimation

To facilitate the estimation of a 4D signal, we applied a global matching filter to match the OBC to the streamer data (computed from a window above reservoir), followed by classical 4D co-processing such as amplitude and time destriping as well as 4D co-denoise. A legacy streamer-streamer 4D comparison was available using a dataset acquired in 2010 in the same area. This enables us to estimate what 4D signal to expect and allows a comparison with the 4D signal extracted from our OBC-streamer comparison.

Figure 6a shows the difference for an inline migrated stack between both (i.e. the 2005 and 2010) streamer surveys. Figure 6b shows the difference between the OBC data and the streamer data from 2005 with receiver-

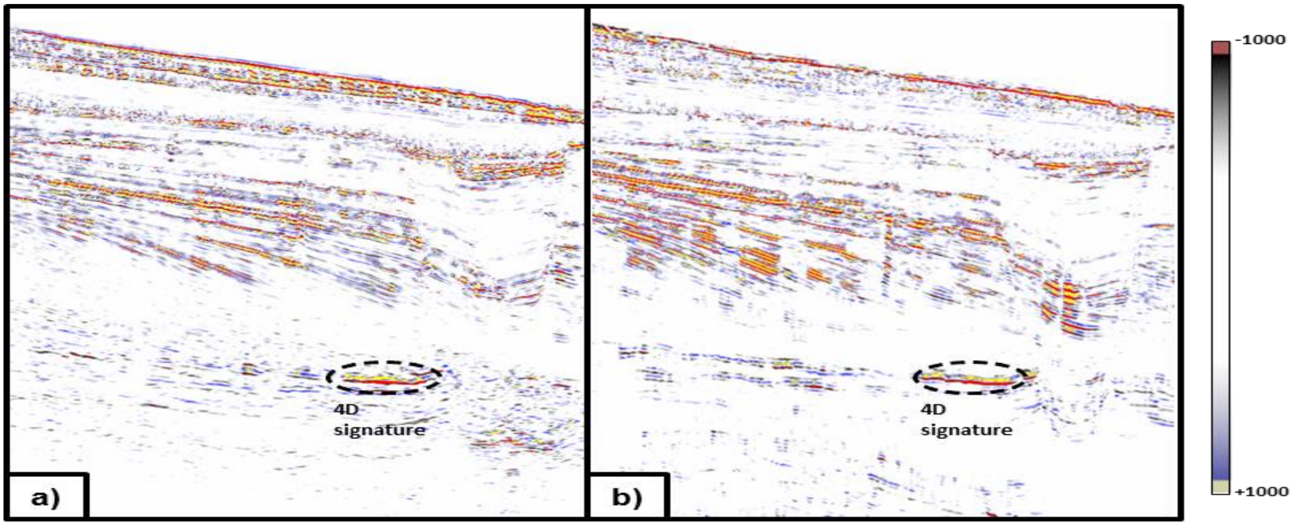

Figure 6 - *4D difference from (a) the legacy streamer-streamer data (b) the cross-spread OBC and streamer data. We see that the new processing sequence for the cross-spread OBC data leads to a final level repeatability comparable to that obtained with streamer data. A 4D signal can be observed that is similar to that observed on the 4D legacy streamer-streamer comparison.*

side ghost-wave elimination. We see that the level of 4D noise is comparable to the streamer-streamer case. Overall, after global matching and 4D co-denoising, an overall NRMS level of 0.15 was achieved, which can be considered reasonable for a comparison between cross-spread OBC and streamer data. Furthermore the 4D signal compares well with what was observed from the streamer-streamer comparison. As such, the proposed processing allows for a qualitative 4D analysis between cross-spread OBC and streamer data.

Conclusions

We showed that by postponing the co-selection to the migrated domain using COV binning, combined with careful 4D de-noising of the OBC cross-spread data during pre-processing, we were able to provide a qualitative 4D signal using cross-spread OBC and narrow-azimuth streamer data from a hydrocarbon field in the Campos basin offshore Brazil. During pre-processing the main causes for 4D noise that were addressed were statics due to positioning errors and water-layer velocity variations, ghost-wave variations and surface-related multiple variations. The preserved azimuthal information in the migrated domain further benefited the 4D de-noising in the migrated domain through the application of azimuthal statics and residual multiple elimination. The estimated 4D signal was comparable to that obtained from two streamer surveys. Overall the NRMS level of repeatability that was obtained was 0.15, which can be considered very good considering the large differences between both acquisition geometries.

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