Introduction
We used an AVO inversion based on the weighted stacking technique described by Smith and Gidlow (1987), and extended for converted waves by Stewart (1990). Examples of the application of this technique can be found in Margrave et al. (1998), on data from the Blackfoot field in Canada, and Zhang and Li (2005), on data from the Ordos Basin in China. The method works by least-square inversion of Aki-Richard’s approximations to recover P- and S-impedance reflectivity ($\Delta I_p/I_p$, $\Delta I_s/I_s$) and pseudo Poisson’s ratio reflectivity ($\Delta \sigma /\sigma$).

The density is assumed to follow Gardner’s relation ($\rho = k\alpha^{1/3}$). Using available log data we verified that this assumption is valid in our area of study.

The weighting parameters are angle-dependent. In single PP-wave inversion, the weights for $\Delta I_s/I_s$ distribute mainly in both the near and far offsets; while for $\Delta I_p/I_p$ the weights decrease with increasing offset. In joint inversion, although the near-offset PP-data and mid-offset PS-data have important weights for both $\Delta I_s/I_s$ and $\Delta I_p/I_p$ estimation, it’s the mid-offset PS-data that have a larger impact on the estimation of $\Delta I_s/I_s$. Incident and reflection angles, time and spatial varying $V_p/V_s$ ratio are calculated from ray tracing through a 1D velocity-depth model.

The reservoir rocks in the study area derive from clastic deep-sea turbidites, mainly consisting of channel sands and basin floor fans. Porosity and permeability are generally good. The overall structure is relatively simple.

Data acquisition and processing
The acquisition was carried out using inline shooting, with swaths of two cables separated by 300 m. The shooting line separation was 50 m. with a shot interval of 50 m. The receiver interval was the conventional 25 m. Data quality was very good, both for P- and C-waves. Time processing via Pre-Stack Time Migration (PSTM) was carried out by a contractor. For C-waves they took particular care of the estimation of the parameter $\gamma_{\text{eff}}$, responsible for the correct structural alignment in the positive and negative offset images (Thompsen, 1999), by performing repeated $\gamma_{\text{eff}}$ scans.

The PZ and PS images for one inline are shown in Figure 1. The PS-waves are displayed in PP-time after event correlation. The correlation was guided by the well log and performed using Hampson-Russel ProMC software. The quality of the two migrated images is good, although we can notice a great difference in frequency content.

Inversion results
Synthetics: We performed synthetic tests based on a geological model derived by blocking the logs from the available vertical well. Synthetic CDP and CCP (C-waves) gathers were calculated using Zoeppritz equations. As shown on the left of Figure 2, the response of the top of the reservoir, indicated by the arrows, has inverse polarity for P and C-waves. This is confirmed by the real data shown on the right of Figure 2, where the main window is for PS-data and the inner window is for PP-data (after band-pass filter in order to make the two sections comparable).
The easily recognizable structure of the area facilitated event registration, which can therefore be considered reliable, above all in the proximity of the well. On these synthetic gathers we tested single (PP-wave only) and joint inversion, with different ranges of offsets and different background velocity-depth models (the original well-derived model and its smoothed version). Results are summarized in Figure 3a, 3b, 3c, and 3d. For each figure, the first two traces are the inversion results for data muted to an offset maximum of 2.5 km (the offset-to-depth ratio is still greater than one and the incidence angle is about 40°). The first of the two traces is for the original velocity-depth model; the second is for the smoothed model. The two traces in the middle of each figure are for the full offset, again with the two velocity models. The last trace on the right is the value derived from the well.

Figure 3a shows $\Delta Ip/IP$ from P-wave single inversion. The results do not change much for the different cases studied. Figure 3b shows $\Delta Is/Is$ from single inversion. In no case can we recover the top of the reservoir, which is the positive peak highlighted by the black line). The inversion seems dominated by the $Ip$ reflectivity. Apart from the top of the reservoir, the best result is given when using full offset (no residual NMO in the synthetics) and the smoothed velocity field. In Figure 3c we show $\Delta Is/Is$ from single inversion of C-wave data. The results are lower frequency as expected but the peak associated to the top reservoir is well recovered. Results with different offsets and velocity models do not show many differences. Finally in Figure 3d we report the results for $\Delta Is/Is$ from joint inversion for the full offset case. The top of the reservoir is again well recovered. The background velocity does not affect the results.

**Real data:** For the inversion of real data we used PSTM CIP gathers and the well derived smoothed velocity-depth model. In Figure 4 we show the $\Delta Ip/IP$ from P-wave single inversion (left) and from joint inversion (right). In this case the single inversion is better, since the joint
inversion is contaminated by the lower frequency content of the PS dataset. In both cases the top reservoir is clearly inverted (black circle).

Figure 4: \( \Delta p/p \) from PP single (left) and joint (right) inversion.

Figure 5 shows the \( \Delta s/s \), again from single and joint inversion. For the S-impedance reflectivity we cannot correctly recover the top of the reservoir (positive peak) when we invert only P-waves. Again, as for the synthetics, the results seem dominated by the P-impedance reflectivity. We run more inversions incorporating further offsets, but with similar outcomes. When using both PP and PS data the inversion correctly recovers the top-reservoir. The image appears lower frequency due to the larger influence of C-waves on the \( \Delta s/s \) inversion. This is also confirmed by looking at the weight distribution.

Figure 5: \( \Delta s/s \) from PP single (left) and joint (right) inversion.

The most convincing proof of the benefits of introducing C-wave data in the inversion can be seen in the results of the pseudo Poisson’s ratio reflectivity, \( \Delta \sigma/\sigma \), given by \( \Delta p/p - \Delta s/s \). In Figure 6 we show the results from P-wave single inversion, on the left, and the results from joint inversion, on the right. While in both cases the anomaly at the reservoir is evident, in the case of joint inversion other gas-related anomalies stand out more clearly. This result should help to increase geophysicists’ confidence during interpretation.
Discussions and Conclusions

We showed results from single and joint inversion of a 4C dataset from West Africa. In this study we made some assumptions and approximations: we used a 1D background velocity-depth model for angle computation, we applied a second-order only NMO correction, we assumed the PSTM to be amplitude preserving and we used Gardner’s relation for density estimation. Nevertheless the joint inversion was stable, also thanks to the good quality of the data. Also we did not try to correct for the footprints typically given by OBC acquisitions, since by working in inlines, given the polarized acquisition, we believe this should not be a major problem.

The results showed that we failed to correctly recover $\Delta Is/Is$ when only P-wave data were used, but we were successful when we introduced C-wave data into the inversion. The weight distribution shows that, in the joint inversion, the $\Delta Is/Is$ inversion is dominated by PS-wave mid-offset data. The results of the pseudo Poisson's ratio reflectivity also look greatly improved when both datasets were jointly inverted. Although these results are encouraging indeed, we always have to consider the main limitation of this inversion scheme, which is the need of event registration. This area was particularly favorable in that sense, since the main structural events are easily recognizable in both sections.

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