4-D Seismic Inversion: A Case Study Offshore Congo

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Summary

The first 4D seismic survey in Congo was acquired over the Moho-Bilondo Field in January 2011, two years and a half after first oil. 4D was expected to help in tracking the movements of injected water inside complex turbiditic bodies and to follow the rise of the oil-water contact. 4D anomalies can be highlighted using seismic attributes such as envelope amplitude and RMS amplitude differences but these standard 4D attributes have a limited vertical resolution and difficulties were encountered to distinguish depletion from water injection. A simultaneous 4D inversion workflow was therefore applied to extend the seismic bandwidth and estimate quantitatively the changes in reservoir acoustic impedance. Spatially variant rock physics constraints were introduced to improve the imaging of the water pathway around key injector wells. Preliminary analysis of the inverted 4D attributes shows an improved image of the fluid movements inside the reservoir compared to conventional 4D attributes.
Introduction

The first 4D seismic survey offshore Congo was acquired over the Moho-Bilondo Field in January 2011, two years and a half after first oil. This first monitor survey (M11) covers an area of 240 km² and has the same bin size of 6.25mx25m as the base survey acquired in 1996 (B96). With an offset length of 3200 meters, three sub-stacks were generated with a maximum angle of incidence of 35°.

Production was initiated in 2008 with eight producing wells on line by the time of the monitor survey. Pressure support is achieved by water injection, with 5 injectors on line at the time of the 4D seismic survey. Time-lapse seismic data are used to help in tracking injected water movements inside complex Miocene turbiditic bodies and to follow the rise of the oil-water contact. Three main areas are contributing to the production: Bilondo, Mobim Horst and Mobim Graben.

Twelve wells with full suite of geophysical logs were calibrated to the seismic data. Rock physics analysis shows that substituting oil by water will create a significant velocity increase. On the other hand, velocity should decrease when gas comes out of solution as pressure drops below bubble point. These velocity changes were expected to be detected from the 4D seismic data. 4D anomalies have been highlighted on seismic attributes, such as envelope amplitude and RMS amplitude differences but these attributes have a limited vertical resolution and are difficult to use for discriminating depletion from water injection. A global multi-vintage inversion technique was applied to overcome these limitations and extract quantitative information from the 4D amplitude data.

We briefly present the 4D simultaneous inversion workflow, and how it integrates a 4D mask and spatially varying rock physics constraints to estimate time-lapse changes in acoustic impedance ($\Delta I_p$). This is followed by an analysis of the 4D inversion results.

4D Inversion Workflow

We use a global inversion scheme where all data vintages are inverted simultaneously (Lafet et al., 2009). Coupling the inversion of base and monitor surveys is important to obtain quantitative estimates of impedance changes and reduce the non-uniqueness of the inversion process. Inversion coupling between successive surveys is achieved using rock physics constraints, honoring expected production effects.

The multi-vintage, global inversion starts from an initial layered model defined for P-wave velocity, $V_p$, S-wave velocity, $V_S$ and density $\rho$ at each survey time. The results of a previous 3D inversion were used to build the initial model for the Base. A composite 4D mask was then defined to specify where the initial model for the monitor survey will be changed. Outside the mask, the monitor initial model will remain the same as for the base seismic. Inside the 4D mask, the initial $V_p$ model for the monitor is updated using a $\Delta V_p$ obtained by applying a warping technique. The warping technique (Williamson et al., 2007) generates a cube of relative P-wave velocity change from the time shift and amplitude changes between the base and the monitor surveys. The density and S-wave velocity initial model attributes for the monitor are determined from the base and from the $\Delta V_p$ using petrophysical relationships.

The “4D mask” was calculated based on a threshold applied to 4D attributes representing the energy of amplitude differences between the two surveys, the warping and the pseudo $V_{\text{clay}}$ volume shown in Figure 1. The pseudo $V_{\text{clay}}$ is a continuous property which represents reservoir quality and is derived from a 3D inversion of the base seismic data.
During inversion, the time-dependent initial model was then iteratively perturbed to find a global solution that optimizes simultaneously the match between the input angle stacks for the two vintages and the corresponding synthetics, calculated by wavelet convolution with full Zoeppritz reflectivity equations.

**4D Inversion Constraints**

4D corridors are used to constrain the range of time-lapse variations of $\Delta V_P$, $\Delta V_S$ and $\Delta \rho$ between base and monitor surveys. These constraints can vary vertically and spatially. Following preliminary 4D inversion tests, unexpected negative $\Delta I_P$ anomalies were observed around injector Well 1. Well 1 started water injection during August 2009; injected water should increase the rock bulk modulus and cause a relatively large increase of P-Impedance ($I_P$) when replacing oil. The effect of a pressure increase on $I_P$ was expected to be of a second order compared to the impact of the saturation change around this injector. Further investigation showed that B96 seismic at this level was affected by seismic noise while the Monitor 2011 does not present this character. The presence of noise is probably explained by the vicinity of a fault affecting the seismic signal. 4D inversion tests using different combinations of angle stacks were conducted to investigate if those inconsistent $\Delta I_P$ were induced by a specific angle stack. The tests showed that the negative $\Delta I_P$ anomalies are not caused by a single angle stack but are related to wavelet side lobe effects. Additional tests with different wavelets were performed to attenuate the side lobes but no convincing results were obtained. In order to find a better solution, different asymmetric 4D constraints were tested around the injector well to drive the inversion towards a positive $\Delta I_P$ solution. A “soft” 4D set of symmetrical constraint was compared to a “hard” asymmetrical set of constraints as described in Table 1. A section of the corresponding $\Delta I_P$ inversion results through the injector is displayed in Figure 2.

<table>
<thead>
<tr>
<th>“Soft” 4D constraints</th>
<th>“Hard” 4D constraints</th>
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</thead>
<tbody>
<tr>
<td>$\Delta V_P$</td>
<td>+/-15%</td>
</tr>
<tr>
<td></td>
<td>-2% to +15%</td>
</tr>
<tr>
<td>$\Delta V_S$</td>
<td>+/-5%</td>
</tr>
<tr>
<td></td>
<td>-2% to +5%</td>
</tr>
<tr>
<td>$\Delta \rho$</td>
<td>+/-8%</td>
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<tr>
<td></td>
<td>-1% to 8%</td>
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**Table 1:** Constraints on the elastic properties used during the inversion.
Figure 2: $\Delta I_p$ results through Well 1 using two sets of constraints.

The impedance anomaly is clearly sensitive to the choice of 4D constraints. As shown in Figure 3, the levels of the seismic residuals corresponding to the “Soft” and “Hard” constraints are about the same, indicating that the two solutions are equally compatible with the observed amplitudes. The “Hard” constraints were therefore chosen as the best solution since they are more in line with the positive impedance change expected around Well 1. A map of this negative $\Delta I_p$ anomaly was made to delineate spatially the application of the “Hard” constraints that was restricted to the vicinity of Well 1.

Figure 3: Energy of the residuals for the Base seismic through Well 1.

4-D Interpretation of Fluid Movements

The analysis of the 4D inversion results provided more detailed information, compared to previous attributes. Figure 4 displays the inversion results between an injector well (Well 2) and a producer well (Well 3). The Pseudo $V_{clay}$ clearly shows the sand body connecting the two wells. Depletion is occurring around Well 3, creating a decrease of the $I_p$ in red. Soft 4D constraints were used between
these two wells to preserve the negative $\Delta IP$ due to depletion. The water influx from the injector to the producer well appears as a positive $\Delta IP$ anomaly.

**Figure 4:** Water pathway from an injector (right) to a producer (left).

**Conclusions**

Implementing 4D elastic inversion has been successful on the Moho Bilondo Field where a better delineation of the water movements was achieved compared to standard amplitude differences. Time-lapse seismic inversion is a non-unique process. The choice of 4D constraints is therefore crucial to guide the algorithm towards a solution consistent with the available rock physics information.

**Acknowledgements**

The authors would like to thank Société Nationale des Pétroles du Congo (SNPC), Chevron Overseas Congo and Total E&P Congo for permission to present the information contained in this paper.

**Technical References**


