Fault shadow zone PSDM Imaging – Entrerrios, Llanos Basin, Colombia

Introduction

The Entrerrios Block is located in the Llanos Orientales Basin in Colombia, with an area of six thousand thirty-eight (6038) hectares. There are three producing formations in the field: Mirador, Gachetá and Ubaque. The main one is the Mirador Formation, which corresponds to continental and transitional deposits of fluvial sands. The Gachetá Formation is made up of punctual sand intercalations with variable content of organic matter. Its depositional environment represents coastal bars and lagoon environments. The Ubaque Formation represents a set of sandstones deposited on the Cretaceous sequence within coastal marine environments with fluvial and deltaic influence.

Geologically the field is part of the Llanos Orientales basin and structurally its configuration was a smooth NE-SW monocline initially. The trap is a combination of structural and stratigraphic factors. The hydrocarbon produced in the Entrerrios field is 16 ° API. Due to the structural and stratigraphic settings and target spatial distribution along the fault shadow zone, the main challenges for a proper target imaging are the mitigation of the fault shadow zone effects at the reservoir level and optimum seismic calibration against the existing well tops (Fagin, 1996; Chermak et al. 2009). The fault shadow effect has been studied extensibility in the Llanos Basin through numerical modelling (Di Giulio et al. 2012).

Thus, the problem that arose was the fault shadow, which did not allow a correct interpretation of the 3D PSTM seismic and its correlation with the depths of the drilled wells; therefore, the structure presented a lot of uncertainty in its configuration, closure, and real position. While time domain processing could not solve these issues, anisotropic PSDM processing, as described in this paper, was successfully used to alleviate the fault shadow effects, even though the offsets were too short to accurately estimate the anisotropy parameters.

Methodology

The Entrerrios-2007 and Entrerrios-2014 3D surveys were processed as a merged 3D, through to PSTM. The acquisition parameters of the two surveys are different as shown on Table 1:

<table>
<thead>
<tr>
<th>Survey</th>
<th>Receiver Interval</th>
<th>Rec. line separation</th>
<th>Source Interval</th>
<th>Source line interval</th>
<th>Source</th>
<th>Bin InLine</th>
<th>Bin XLine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrerrios-2007</td>
<td>40m</td>
<td>240m</td>
<td>80m</td>
<td>360m</td>
<td>dynamite</td>
<td>40m</td>
<td>20m</td>
</tr>
<tr>
<td>Entrerrios-2014</td>
<td>54m</td>
<td>76-4m</td>
<td>54m</td>
<td>972m</td>
<td>dynamite</td>
<td>40m</td>
<td>20m</td>
</tr>
</tbody>
</table>

Table 1 Acquisition parameters for Entrerrios-2007 and Entrerrios-2014 3D surveys.

Upon successful PSTM completion, the interpretation process identified 5 main target horizons (Leon, Carbonera 1, Mirador, Ubaque, Basement) and 7 wells (tops and VSP/Sonic for Entrerrios #1, #2, #3, #5, #6, #7, #8) which formed the “skeleton” of the PSDM initial velocity model.

The initial isotropic PSDM interval velocity model was built starting off with the final PSTM velocity model calibrated with the VSP/Sonic velocities. With this initial velocity model, a Kirchhoff PSDM was applied on a 120 x 120 m grid. The tomographic iterative workflow to update the velocity model used the following steps: automatic picking (selection of back-projection points for which coherency and dip are calculated), moveout analysis (semblance analysis & picking), back projection points, tomographic updates (matrix building and velocity model update).

Four inline and four crossline sections through the well locations were chosen to monitor the progress of the tomography updates.

The first velocity model isotropic tomographic update was performed from surface to the top of Leon Shale layer, creating Model 1 (see the tomography parameters on Table 2). Similarly, the second velocity model isotropic tomographic update was performed from surface to the Basement horizon, creating Model 2 (completing the isotropic velocity model updates). The result produced both good imaging of stacks/gathers above Leon Shale layer and good calibration with the tops of the existing wells above Leon Shale layer and systematic consistent differences to the tops below Leon Shale (see Figure 1). Also, the VSP curves matched nicely the PSDM velocity model trend. The fault shadow zone effects are still present and will be tackled during the TTI fault-constrained tomography.
Fault shadow zone PSDM Imaging – Entrerrios, Llanos Basin, Colombia

<table>
<thead>
<tr>
<th>Iteration/Model</th>
<th>Description</th>
<th>Tomography Grid Size</th>
<th>Semblance Smoothing</th>
<th>Inversion Smoothing</th>
<th>Max Velocity Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Model (Model 0)</td>
<td>Isotropic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>Isotropic (From surface to top of Leon shale)</td>
<td>150 x 150 m</td>
<td>800 x 2400 x 2400 m</td>
<td>500 x 1000 x 1000 m</td>
<td>10</td>
</tr>
<tr>
<td>Model 2</td>
<td>Isotropic (From surface to Basement reflector)</td>
<td>150 x 150 m</td>
<td>800 x 2400 x 2400 m</td>
<td>500 x 1000 x 1000 m</td>
<td>10</td>
</tr>
<tr>
<td>Model 3 (Initial anisotropic model)</td>
<td>TTI Anisotropic (Fault constrained)</td>
<td>150 x 150 m</td>
<td>800 x 2400 x 2400 m</td>
<td>500 x 1000 x 1000 m</td>
<td>10</td>
</tr>
<tr>
<td>Model 4</td>
<td>TTI Anisotropic (Fault constrained)</td>
<td>150 x 150 m</td>
<td>800 x 2400 x 2400 m</td>
<td>200 x 1000 x 1000 m</td>
<td>5</td>
</tr>
<tr>
<td>Model 5</td>
<td>TTI Anisotropic (Fault constrained)</td>
<td>150 x 150 m</td>
<td>800 x 2400 x 2400 m</td>
<td>200 x 1000 x 1000 m</td>
<td>2.5</td>
</tr>
<tr>
<td>Model 6 (Final Model)</td>
<td>Same as Model 5 with improved basement velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Summary of tomographic update parameters.

Model 3 was built by freezing the isotropic velocity field above Leon Shale, introducing the velocity inversions between Leon and Carbonera 1 layers as well as below Carbonera 1 as indicated in Entrerrios #1 well, and scanning for delta and epsilon anisotropic parameters. The determination of the spatially varying delta and epsilon, produced the anisotropic regime described in Figure 2. It was also determined that a vertically varying epsilon field is necessary: 6-8% down to 2.5 km and 1.5-2% below 2.5 km. The PSDM result confirmed the accuracy of the Model 3: the fault shadow zone effects were mitigated, while the seismic vs. well tops analysis showed in Figure 2 below produced an average mistie of 0.20%.

Figure 1 Final isotropic model (Model 2). (a) velocity model. (b) Inline section in the area of the fault shadow. (c) CIG gathers at the locations indicated by the red arrows.

Once the anisotropic delta and epsilon parameters were set, the faults were interpreted to create the constraint condition for the anisotropic fault-constrained velocity model tomographic update, creating velocity Model #4. The purpose of fault-constrained tomography is to create a data input condition that would allow the inversion algorithm to focus only on one side of the fault without interference from the other side of the fault. The PSDM results with Model 4, show that the fault shadow zone effects were further mitigated, while the seismic vs. well tops analysis produced an average mistie of 0.01%.
Fault shadow zone PSDM Imaging – Entrerrios, Llanos Basin, Colombia

![Figure 2](image1.png)

**Figure 2** (a) fold map and wells. (b) spatially gradient of delta & epsilon. (c) mistie analysis for Model 3 with final delta and epsilon fields. Average mistie = 0.20%.

![Figure 3](image2.png)

**Figure 3** Initial anisotropic model (Model 3). (a) velocity model. (b) Inline section in the area of the fault shadow. (c) CIG gathers indicated by the red arrows.

Since the residual analysis showed a robust and converging solution, the next velocity model Tomographic update (velocity Model 5), fine-tuned the velocity field keeping the same general parameters as Model 4, but with maximum velocity variation of 2.5%. Due to limited long spatial offset distribution, further velocity model improvement was achieved by scanning with different local (Basement and below) assigned velocity values and determining the optimum velocity (4,300 m/s). The procedure created the final velocity Model 6. The PSDM result led to better resolution of the target zone as well as a very low mis-ties between seismic and well tops as follows: Leon = 0.17%, Carbonera 1 = 0.04%, Mirador = 0.12%, Ubaque = 0.29% and a total average mistie of 0.08%.

![Figure 4](image3.png)

**Figure 4** Final anisotropic model (Model 6). (a) velocity model. (b) Inline section in the area of the fault shadow. (c) CIG gathers indicated by the red arrows.
Fault shadow zone PSDM Imaging – Entrerrios, Llanos Basin, Colombia

To illustrate the improved image in the fault-shadow zone, Figure 5 shows a comparison of the inline shown in Figures 1, 3 and 4 from the PSTM volume (converted to depth with the initial velocity model) and the corresponding inline section from the final anisotropic PSDM. The area enclosed by the rectangle shows that although the fault shadow effect has not been completely eliminated, it has been reduced to a point where a correct interpretation can be carried out.

Figure 5 Comparison of depth converted PSTM (a) with final PSDM section. Notice that the fault shadow effect (inside the rectangle) has been greatly reduced.

Conclusions
Anisotropic PSDM proved to be a powerful tool to correct for the fault shadow effect in this dataset, even though the offsets were very short compared to the depth of the reflectors (as indicated in panel (c) of Figures 1, 3 and 4). The seismic well tie went from an average error of about 2 to 3% in the isotropic model to about 0.1% in the final anisotropic model. The Results of the PSDM processing and its subsequent interpretation permitted correcting in a very good way the effect of the fault shadow, allowing to observe and interpret the field as a monocline compartmentalized by faults of preferential direction SW-NE of greater size and quite different configuration; this has brought a strong benefit in finding a larger area of the field, which is reflected in an increase in on-site reserves and the possibility of drilling new development and advanced wells in better structural positions that the well previously drilled in the field.

Acknowledgement
We thank Petroleos Sudamericanos Energy for permission to process the seismic data and present this paper.

References