Simultaneous Joint Inversion as a Salt Detector in South Gabon Land Exploration*

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Introduction

Hydrocarbon exploration in the South Gabon sub-basin produced many large oil discoveries; yet an accurate depth map of the pre-salt objectives remains elusive. Vertical relief at base salt horizon -the ultimate seal- is often less or equal to the uncertainty inherent in the depth map construction. For existing fields, depth maps guided by wells only are preferred to seismic-based depth maps. For exploration, because a seismic-alone method was failing, Perenco hypothesized that gravity data could be utilized to enhance the imaging of pre-salt seismic reflectors by providing additional input for prestack depth migration (PSDM). As a test, two vintage 2D seismic lines were reprocessed utilizing simultaneous joint inversion technology developed by WesternGeco. After a brief description of the geological setting, we discuss the gravity data input into the workflow. The PSDM joint inversion workflow is detailed. The application of this technique in a salt context discloses how the interpretation can be guided by deviation from Gardner's rule (Gardner et al., 1974) , and encouraged Perenco and its partner to pursue application of this workflow to a complete set of 2D seismic data covering the area of interest.

Geological Setting

Thick, Barremian, rift-phase Dentale Formation sands and shales are overlain by the discordant Gamba sandstones. This sequence is overlain by the Aptian Ezanga evaporitic sequence, which provides the ultimate top seal for Gamba or Dentale sandstone reservoirs. A thick and complex Madiela carbonate layer forms the rest of the overburden. Changes in Madiela facies and thickness, both vertically and laterally, lead to a poorly defined velocity model for this layer. The Lower Madiela often presents velocities similar to the Ezanga salt formation, resulting in a weak top salt seismic event. To add to the complexity of the overburden, clastic cuvettes, filled with low-velocity sediments, develop as a result of salt withdrawal (Figure 1).

Gravity Input Data

Gravity measurement, not subject to the wave propagation problems affecting seismic data in such overburden, fills the gaps along the seismic profile. Prior to this study, joint inversion was applied utilizing only land gravity data. Airborne gravity was considered suboptimal because its resolution and accuracy is a log value poorer than the land gravity. However, forward modelling showed that airborne gravity was capturing the gravity variations generated by the clastic cuvettes and the alternation of Ezanga mounds with Madiela turtlebacks (Figure 2). The gravity data were acquired along N-S lines spaced by 250-m E-W tie lines were acquired every 2500 m. After levelling, the gravity data underwent two stages of processing. First, a low-pass line filter was defined in time, and then a spatial filter was applied to the gridded data. Using the forward-modelling results, we concluded that the input with a 10-s line filter and 750-m spatial grid filter was most fit for purpose because a good level of "noise" suppression was achieved without removing the expected high-frequency, low-amplitude signal variation.

Simultaneous Joint Inversion Methodology

Close interaction between WesternGeco and Perenco allowed convergence towards a realistic input model for the joint inversion. The initial data-driven model challenged the Perenco geophysicist's seismic interpretation. Joint inversion was used as a sensitivity test on the seismic interpretation and allowed elimination of non-geological scenarios, but preserved geophysically plausible scenarios and vice versa, according to the workflow schematized in Figure 3.

Seismic imaging in depth often results in the paradox of having the correct interpretation at the beginning of the job, where interpretation is the objective of the seismic technique, and not the reverse. The quality of a prestack depth-migrated image may depend on a number of factors and opinions. Apart from this, geophysics does not offer a quantitative QC tool for interpretation except expensive exploration drilling. A broad number of valid velocity solutions that flatten the PSDM gathers may not solve interpretation ambiguities at all.

A Non-Gardner Indicator

Gardner et al. (1974) proposed a density and velocity relationship widely valid for a a number of lithotypes. In the special case of non-Gardner (N-G) bodies (i.e., salts) inside a standard Gardner background setting, joint inversion offers a quantitative approach to QC where interpreted layer boundaries for such a formation can be refined in an iterative, trial and error process. Misplacements or boundary errors in N-G horizons result in joint inversion velocity and density outputs as inconsistencies that may, therefore, indicate layer geometry corrections to otherwise regular solutions.

For the described case of Gabon reprocessing, the starting setup of joint inversion is largely sensitive to the interpreted boundary for Gardner rule validity. Relying on the well logs (Figure 4), Ezanga salt diverges obviously from the otherwise positive Gardner relationship and a modified alpha and beta Gardner parameter is derived for joint inverting this formation.

Away from salt, clastics and Madiela formations are positively correlated in terms of Gardner, so the anomaly distribution should show similarity between the velocity and density fields. A cross-gradient control is used together with Gardner to invert these layers. Regarding the salt, the anti-correlation effect (Figure 4) pushes joint inversion into an interpretation-driven solution, introducing simple artifacts that are then used to drive interpretation into a gravity-consistent salt shape.

After a complete joint inversion run with reasonable residual error, the expected anti-correlated cross-relation between velocity and density is not achieved for all the interpreted salt bodies (Figure 5). This violation reveals a misplacement of N-G modeled bodies with respect to the real position and shape of the Ezanga. A missing salt effect results in the model with a low-density anomaly having abnormal intensity and squeezed into overlying close layer boundaries, with unjustified light tail fed into the layers below (Figure 5, salt bodies 2 and 5). An over-estimated salt effect results in an apparently Gardner-correlated behavior within the N-G modeled layer (Figure 5, salt bodies 4 and 6).

Interpretation is updated to accommodate the observed discrepancies and the desired anti-correlation is achieved. Reduction of system uncertainty is achieved directly during interpretation, without passing from image evaluation. The described capability to detect the best-fitting N-G boundaries represents a unique solution for layer tuning and identifying interpretation inconsistencies.

Conclusion

Where previous interpretation within the pre-salt section was limited by poor imaging, particularly beneath salt mounds (Figure 1), reprocessed lines now offer continuity (Figure 6). The new data validate Dentale correlation between wells, and allow a better understanding of faulting and structure within the Dentale. Base salt depth might not be yet absolute, but future processing of a dense network of lines will pinpoint relative base salt highs. Independent of the joint inversion, a depth-to-basement map was derived from the aero-magnetic data acquired along with the gravity data. The depth-to-basement map produced by Earthfield Technology using the Werner (1955) deconvolution method explains the rotated fault block in the centre of Test Line 1. It is linked to a basement step.

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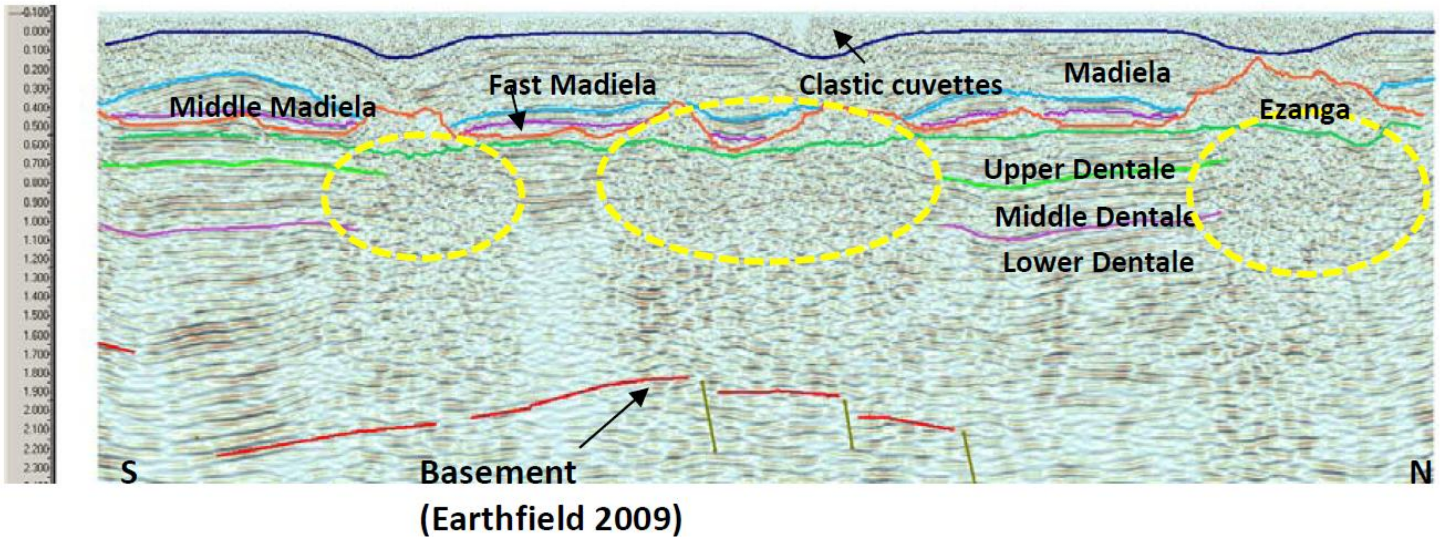

Figure 1. Vintage PSTM seismic Test Line 1. No pre-salt imaging below salt mounds.

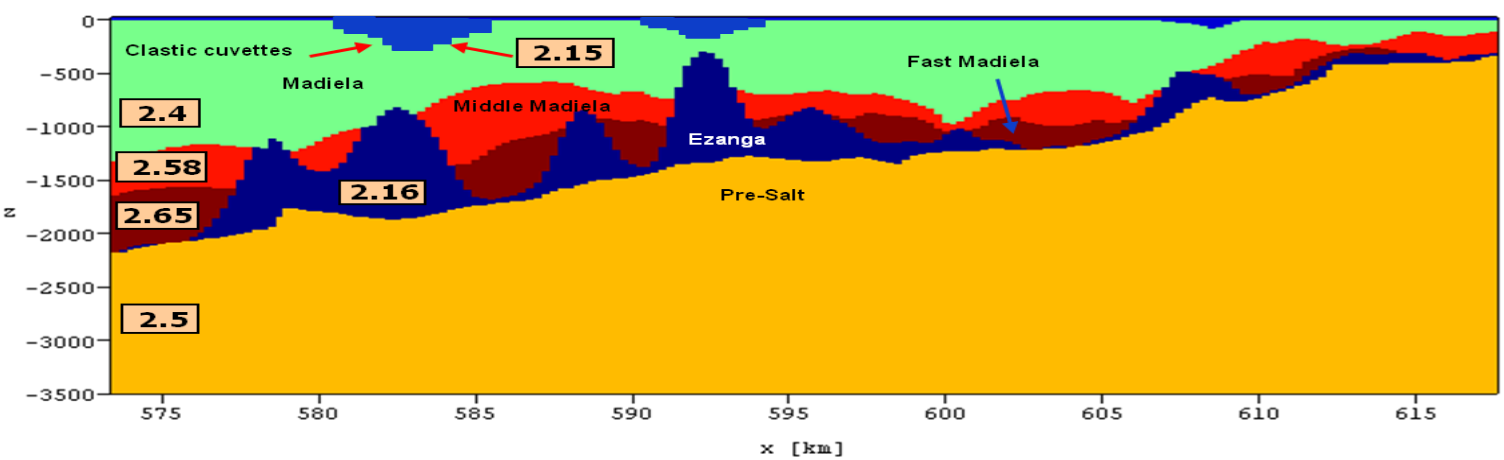

Figure 2. Gravity model along Test Line 2 used for gravity forward modelling.

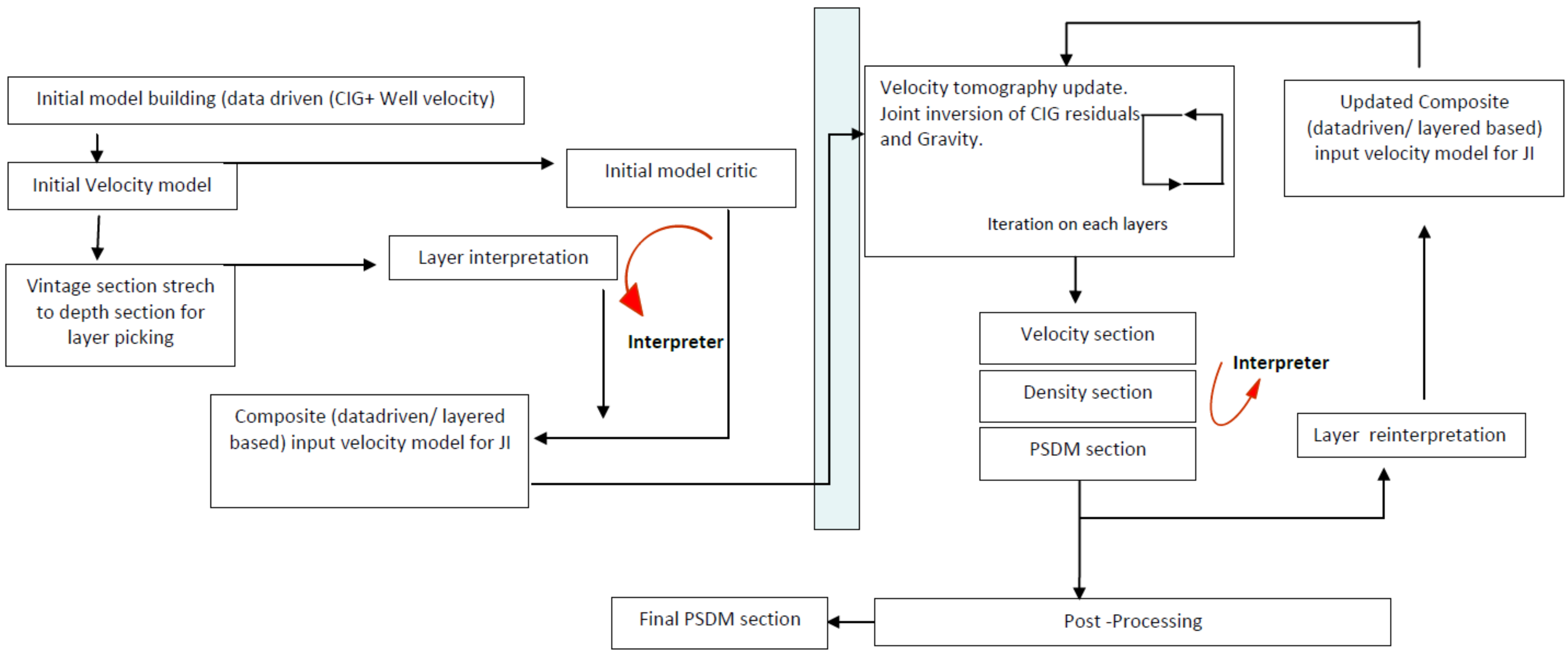

Figure 3. Joint inversion integrated workflow between interpreter and processor.

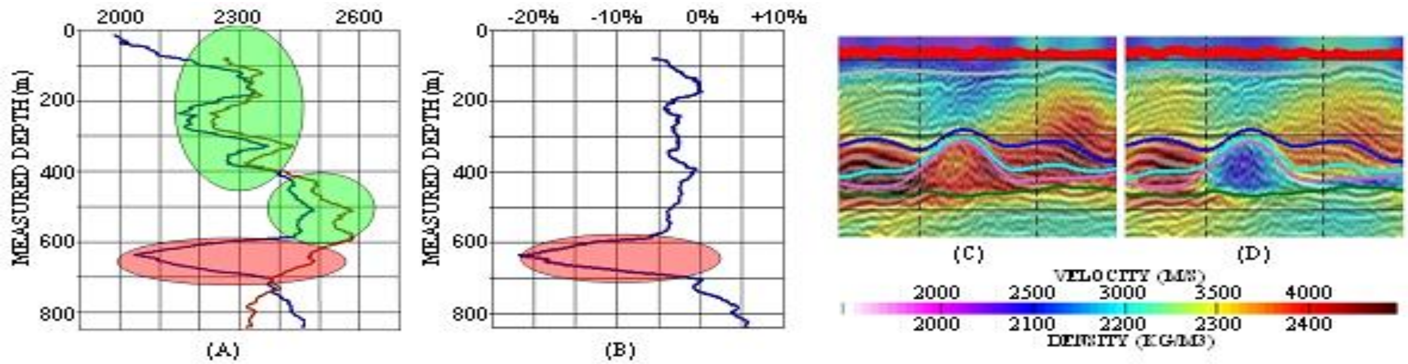

Figure 4. (A) Density derived from Gardner-converted velocity (red) vs. measured density (blue). Green circled good fit area corresponds to Upper and Fast Madiela; red circled misfit is Ezanga salt. (B) Percentage error of the two curves in (A). (C) and (D) Joint inversion behaviour on a Ezanga salt dome with clastics and Madiela in background; (C) Velocity section; (D) Density section. Note the good geometrical correlation between the sections except for Ezanga, which is anti-correlated.

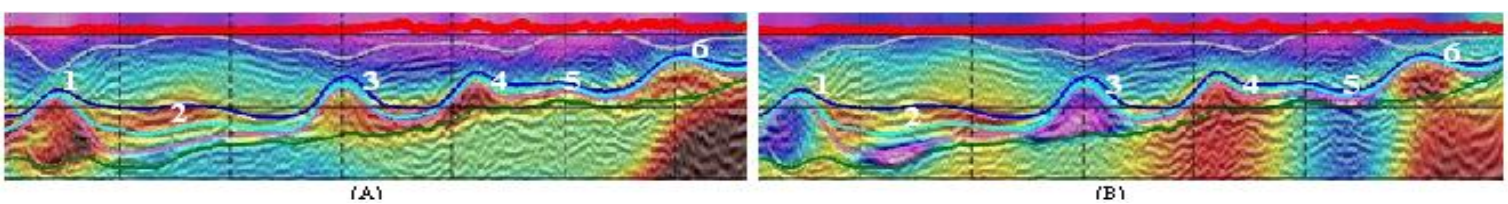

Figure 5. (A) Velocity and (B) Density from joint inversion. 1 and 3 are real Ezanga salt, whereas missing salt in interpretation is hinted at 2 and revealed at 5. 4 and 6 are false salt (folded Madiela).

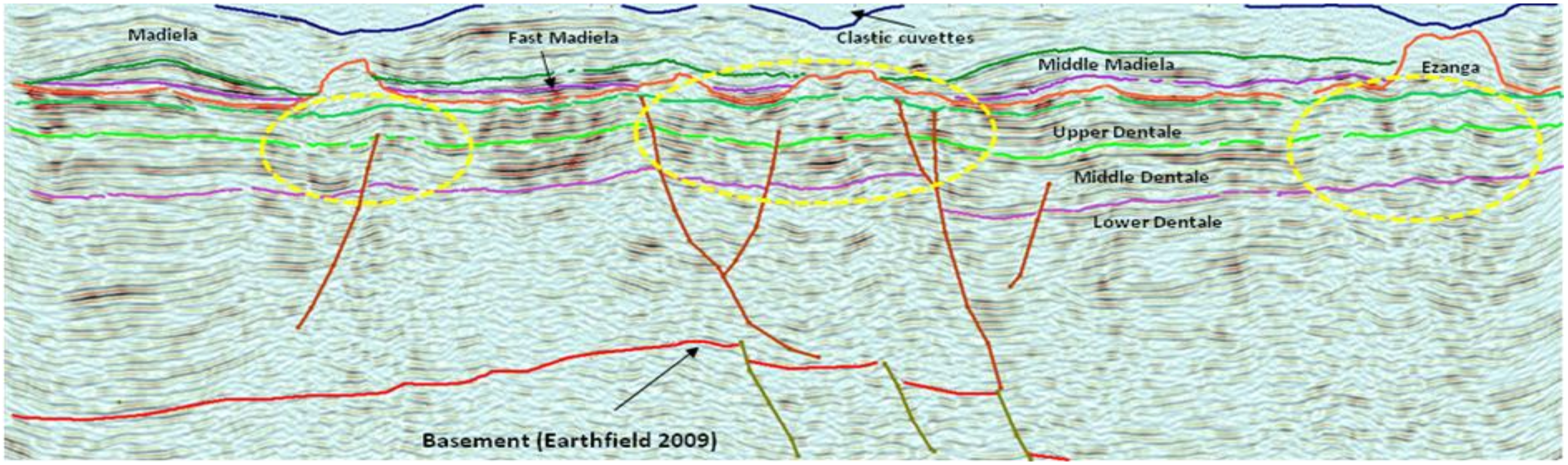

Figure 6. PSDM seismic Test Line 1, converted back to time.