Combined pre-stack and post-stack interpretation for velocity model building and hydrocarbon prospectivity: a learning case study from 3D seismic data offshore Gabon

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Introduction

We present an integrated geological and geophysical study conducted during the acquisition and processing of extensive 3D Multi-Client seismic campaigns offshore Gabon. These campaigns resulted in two distinct surveys, the first of 11.500 km^2 in the southern shelf, and a second of 5500 km^2 to the north, offshore Libreville (Figure 1). The acquisition parameters and survey design were planned with seismic illumination studies, long offset streamers were utilised and the data was processed with a modern broadband sequence (Esestime et al., 2017).

The surveys presented various imaging challenges, from shallow water multiples to shallow high velocities, carbonate and salt. The Gabonese Authorities for Hydrocarbon (DGH) provided a comprehensive well dataset, including geological markers, logs and checkshot data. These penetrated both pre-salt and post-salt sections, and provided valuable data during all stages of the velocity model building, especially for the southern part of the area. Well data was more limited for the northern survey, where previous exploration stopped mainly in the post-salt shallow section and velocity logs are limited to a few wells.

The continuous iteration of geological information at every stage of the processing allowed an integration of the geological information at multiple stages. In particular, pre-stack and post-stack analyses allowed for determining regional petro-physical properties, such as 'recurrent velocity trends' which are useful to interpret at multiple scales from post-stack to single gather data.

We obtained accurate seismic velocities, regionally consistent with the geology from sparse wells. Excellent seismic-to-well tie was achieved on the final depth data in South Gabon, from wells 50-70 km apart, in a highly variable structural-stratigraphic setting, dominated by tectonics and salt movement. The results provided a strong learning curve for analysis and QC of several intermediate velocity models obtained from the tomographic updates during the depth migration exercises (Kirchhoff PreSDM).

The new image of hydrocarbon prospectivity

Two major petroleum systems are present offshore Gabon, separated by mobile evaporites known as the Ezanga Formation, and having discrete source rock/reservoir pairs. The pre-salt petroleum system lies in the syn-rift, and early post-rift sequences that were deposited during the break up of the conti-

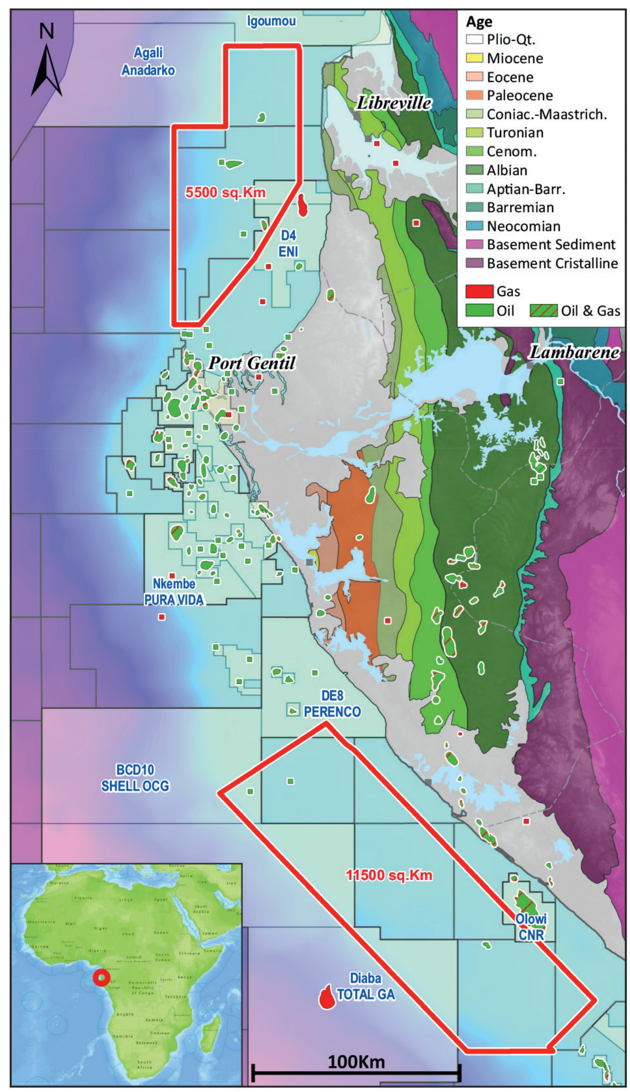

Figure 1 Map showing the Spectrum`s Multiclient 3D seismic surveys offshore Gabon. Onshore geological map in the background (Thomas et al., 2001).

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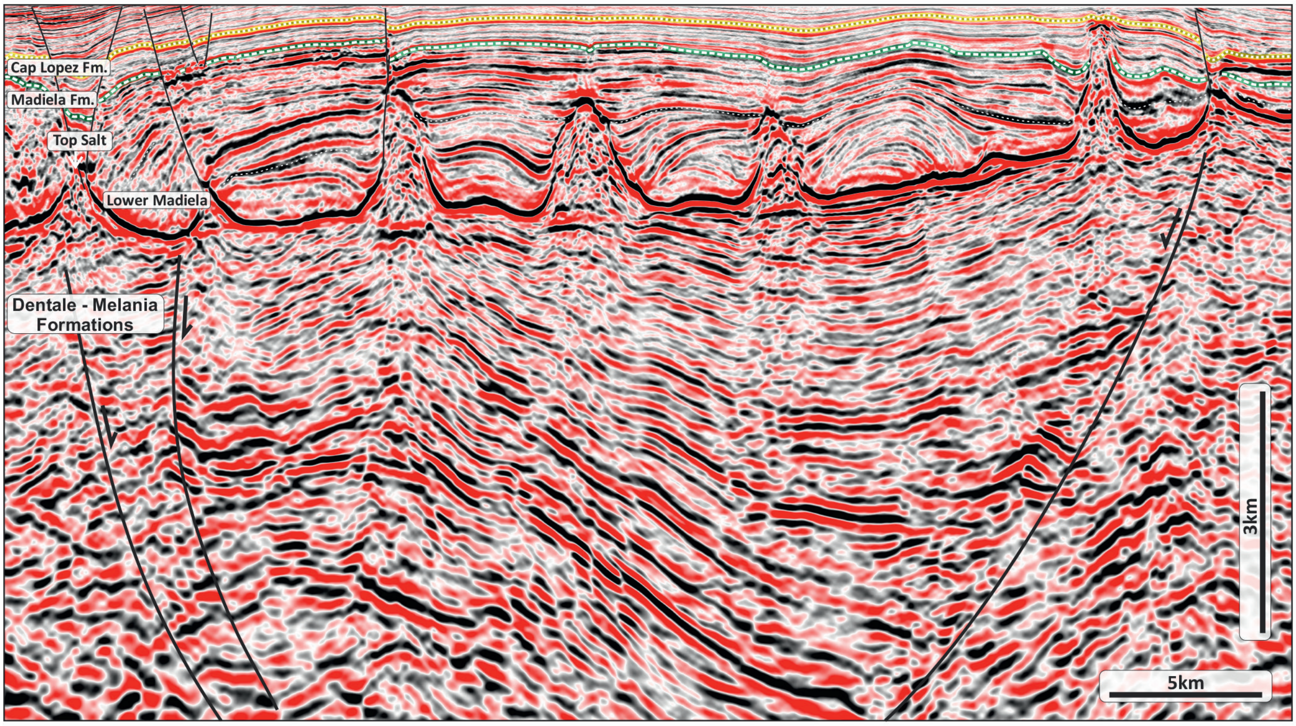

Figure 2 Depth seismic profile extracted from the southern 3D survey. The section is obtained by an algebraic combination of the final RTM (Reverse Time Migration to 30 Hz) with near and middle angle stacks from the Kirchhoff PreSDM. (The same final velocity model was used in both migration algorithms.)

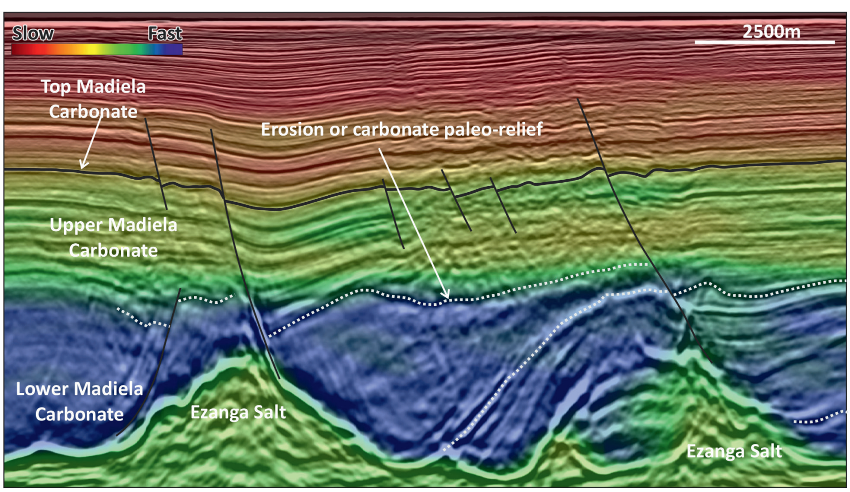

Figure 3 Seismic overlay of the Final Velocity Field with Kirchhoff PreSDM in depth. The velocity field allows characterizing different facies within the Madiela Carbonate. The stratified limestones of the upper section are slower and potentially more rich of siliciclastic deposits. The lower section shows seismic velocities up to 6000 m/s and is dominated by massive carbonate and dolomites (Lower Madiela).

nent of Gondwana in the Early Cretaceous period. The post-salt petroleum system comprises the sediments deposited during continental drift of the West African passive margin. Each petroleum system has been characterized historically by various source rocks, reservoirs and trapping mechanisms (Teisserenc and Villemin, 1990).

In South Gabon, the new 3D data reveals a startlingly clear image of the pre-salt syn-rift play systems, which previous generations of legacy seismic data have failed to resolve. Sitting just below the salt, the transgressive Gamba Sandstone play relies on subtle low relief topology forming 4-way or fault bounded structures. The difficulty of mapping such structures in the past is largely responsible for the previous dry wells (Esestime et al., 2018). However, the Gamba Sands are no longer the only exploration objective as deeper intra-syn-rift targets are now revealed.

Structural mapping of the new 3D data shows a complex pattern of syn-rift structures, characterized by extensional faults on an en-echelon trend with strike direction between N-S and NW-SE. These listric roll-over anticlines (which may have a transpressional component) create large 4-way dip closures, each with areal closure of more than 150-200 km^2 (Figure 2). The syn-rift units of the Lower Cretaceous are imaged down to 10 km depth, showing fluvial and lacustrine sediments deposited within an active rift-graben. Multiple source rocks are present, at various depths, and with different levels of maturity, generating mainly oil from the Dentale, Melania and Kissenda formations. Fine-grained source rocks are interbedded with multiple sand layers, characterized as a distinctive seismic facies, indicating stacked targets for future exploration. The intra-syn-rift structures are not coincident with overlying Gamba Sandstone targets so that within the 3D area we can identify only one valid test of this intra-syn-rift play. The Muruba-2 well was drilled in the early 1980s proving the play in the L. Dentale Formation/Melania Formation with two pay-zones of 20% porosity, which flowed a cumulative 1800 BOPD oil.

Within the post-salt petroleum system there are also multiple source rocks and both carbonate and clastic reservoirs, while in the shallow waters of Gabon's southern margin the post-salt cover is not thick enough to push these post-salt source rocks into the oil widow. In the north and throughout the Ogouee Delta this post-salt oil rich petroleum system has provided the main plays that have been exploited prolifically in the past.

Halokinesis varies in character from South to North Gabon, and from east to west. In the south and east of offshore Gabon, salt bodies are rare and comprise diapirs and remnant salt walls separated by welds where subsiding post-salt sits on very thin salt over pre-salt Vembo shale and Gamba sandstone. Outboard to the west and north of the Ogouee Delta where thick allochthonous salt has accumulated, columnar and tear-drop diapirs and large salt walls are observed, creating salt-wall flanks and even sub-salt canopy structures.

Madiela Carbonate is present in the lower section of intra-salt-pods and in the inboard areas, where shallow water conditions may have been preserved during salt withdrawal. To the south, the main phase of salt withdrawal was largely completed by the Albian, leaving a more stable substratum, where the Madiela Carbonate eventually formed a regional carbonate platform (Upper Madiela). Carbonate sedimentation ended regionally with transgressive marly limestones (Cap Lopez Formation), followed by Paleogene-Neogene shales and sandstones.

The detailed characterization of the Madiela Carbonate, has been a basic requirement for the velocity modelling, in both the southern and the northern 3D survey, having seismic velocities up to 6000 m/s. These shallow-water carbonates were deposited during the thermal subsidence of the passive margin. They were organized in a variety of facies controlled by the salt withdrawal, especially in the lower interval where shallow water facies remained confined within salt-pods or in salt-rafts (Lower Madiela) and are identified by the highest velocities from seismic tomography (Figure 2).

In north Gabon, carbonate sedimentation coexisted with an active deltaic system, in mixed facies, gradually more clastic in the upward section of the Turonian-Maastrichtian. Meanwhile, channelized bodies are present at different levels. This section has a variety of seismic and lithological facies controlled by salt movements, mostly unexplored, and includes proven reservoir conditions in the few discovery wells from the past (Topaze – 1, Oyan Marine – 1 and Iguega Marin – 1).

Pre-stack and post-stack interpretation workflow

Seismic velocities are one of the primary attributes to relate the petrophysical properties extracted from the geology to the events on a seismic profile. The most common practice is the identification of events with good similarity through the offset (semblance picks). In this workflow the velocity information is extracted from either parametric i.e. Normal Move Out (NMO) or non-parametric event picking. The procedure is in itself a form of seismic interpretation, with RMS and interval velocities being related (Dix, 1955) and the selected events having a perceptible effect on the resultant velocity field. Gather picks can be done manually or automatically, e.g. tomographic models and ray tracing. When each gather is computed or picked separately, noise and spurious events, residual multiple, PS converted waves, refraction etc, along with rapid lateral variation in the overburden, will contribute to an incorrect estimate of the velocity field. Eventually, post-stack horizons may be added on the gather as a guide for the operator, or to correlate among them (Esestime et al., 2016).

The standard design of long-offset seismic data helps to obtain a more accurate estimate of the velocity in an 8 to 12 km distance, up to higher orders of NMO (Grigorova, 2015). However, even prior to the waves going critical, the presence of noise and multiples can be a large limitation to the offset visibility, especially in the far traces, where various types of multiples can be concentrated. In areas with high signal-to-noise ratio, the tomographic updates (Kirchhoff based workflows) have shown to successfully resolve large velocity errors and are used to supplement conventional reflection-based tomography (Gong et al., 2018; Liu et al., 2018).

Long offsets in model building are especially beneficial for diving wave-based full waveform inversion (FWI), where penetration and depth of updates are related to cable length and subsurface response. For pre-salt and sub-salt model building, various extensions to wave equation imaging have been presented where RTM stack, partial stacks and angle gathers provide much better image and higher angles to work with. More recently least squares RTM and reflection-based FWI have been proposed by a number of authors (Kiao et al., 2016).

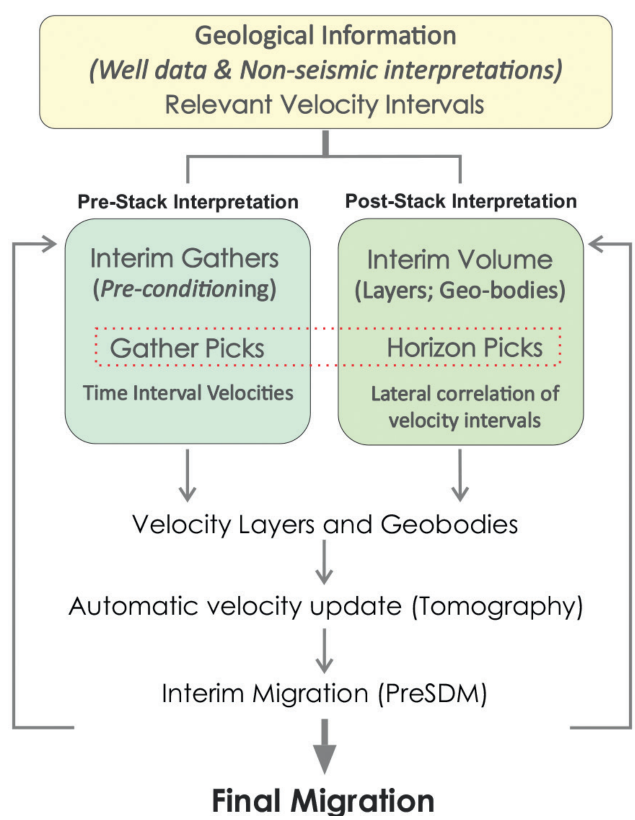

Figure 4 Simplified workflow for pre- and post- stack interpretation.

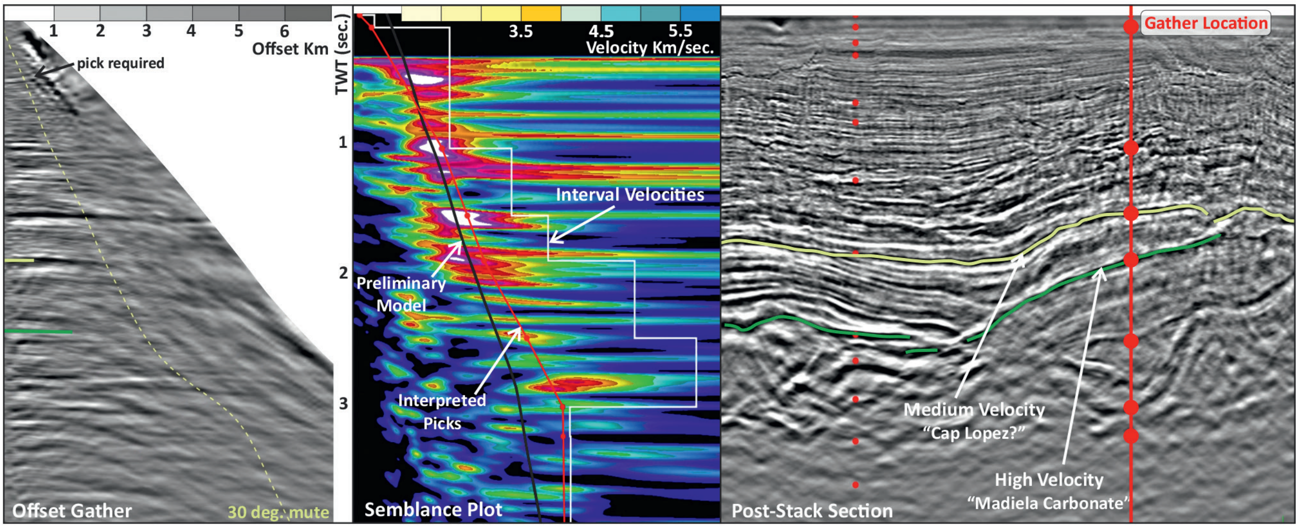

Figure 5 Gather picks obtained from the interpretation of the main velocity breaks.

To approach a geological interpretation of the gather, several velocity interpretations may be trialled to test the interval velocities of different geological scenarios and stratigraphic setting. Well locations can be the starting points from which the gather analysis is performed, especially if provided with check-shot data, sonic and stratigraphic logs. The creation of well-to-seismic match and synthetic gathers can be beneficial, though not mandatory. The analysis has to follow a level of detail driven by the stratigraphic complexity, the number of wells and the distance among them. DIX is unreliable circa 200 ms so the horizons must be controlled and sparse, and tie with major lithological contrasts. This procedure is analogous to the building of a low-frequency background model from velocity for a seismic inversion, but with the high-frequency velocity information extracted directly from the gathers picks.

The interpretation is primarily aimed at obtaining the best stack from the gather. The semblance displays may help to locate the picks, but only the trace flattening is relevant, because noise and multiples may mask the main velocity breaks from the semblance. The total number of picks is usually lower than those automatically made for modelling, and it is important to choose geologically sensible units for these. Additional intervals can be identified if required from some of the gather segments. The procedure is similar to horizon picks from a stack, and the use of these can help to extend laterally the velocity intervals identified.

In the southern 3D data, major velocity breaks were cut to four main intervals identified by formation tops and homologous seismic markers: top Cap Lopez marls, top Madiela, top Lower Madiela, top and base Ezanga Evaporites. The carbonate velocities had a very distinctive trend, with evident reflectors at the main velocity breaks in both gathers and well data. That helped the tomography to gradually converge to reasonable velocities for the carbonate and the overburden section. Well data and related gather location were just used to QC the progress. Salt velocities did not represent a main challenge, as these evaporites have tight ranges of velocities, of approximately 4000 m/s.

To obtain a similar level of confidence in the north Gabon survey, the geological interpretation from the gather has been developed to a more extensive level of detail with various post-salt scenarios. Despite the lack of well data, sections and gathers have displayed good quality markers, since the early stages of the time processing. A number of geological scenarios have been tested to flatten the data; high velocity levels, which are common in the Lower Madiela, have been found in the lower section of the mini-basin. Here, a slow overburden of 2000-3000 m/s, is juxtaposed on allochthonous salt bodies.

Conclusion

NMO velocities are always relative and migration velocities are expected to be closer to the ground truth. We have presented a holistic approach to combine migration and stacking velocities by integrating geological information.

Where geological information is available, the NMO picks can be used as a 'scanner' to evaluate the interval velocities and to interpret the geological extent of intervals and geo-bodies.

In the absence of or with limited well control, stacking velocities should be made consistent with geological intervals identified from well data or other geological/geophysical data. Interval velocities obtained from pre-stack interpretation can be calibrated at well locations, or using regional knowledge about the stratigraphy and the structural setting. The interpretation can be set to an appropriate level of detail, depending on the extent of the seismic data, the geological complexity, and the level of confidence on the calibration.

The workflow can be used to assess the accuracy of existing migration fields, especially in the case of seismic tomography and other forms of automatic modelling.

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