Shallow water Gabon 3D: focused processing images pre- and post-salt prospectivity

Paolo Esestime[1*], Howard Nicholls[1], Karyna Rodriguez[1], Neil Hodgson[1] and Laura Arti[1] describe an integrated geological and geophysical approach applied to time and depth seismic imaging.

Introduction and 3D seismic plan

In 2017 Spectrum conducted a major 3D seismic acquisition programme of approximately 11,500 km^2 in shallow water offshore South Gabon (Figure 1). The project was carried out in close collaboration with the Gabonese Authorities (*Direction Generale des Hydrocarbures*; DGH) and was driven by renewed interest in a proven hydrocarbon province. Continuing exploration since the 1960s has proven all the key elements: source rock presence and maturity, reservoir presence and effectiveness, seal and oil charge into structural and combined structural-stratigraphic traps. Indeed, many oil fields, such as the Olowi Field, have been discovered and are producing in the onshore and nearshore.

Like other Central Atlantic Margins, the geological evolution created two completely different geological settings offshore Gabon, subdivided by a mobile layer of evaporites, which separate the syn-rift section from the post-rift. Each section has a different paleo-geographic evolution, both with oil-prone source rocks. Carbonate and clastic reservoirs have been proven in the post-salt; good quality sands (Gamba and Dentale Fms.) are also proven in the very late syn-rift.

In the past, hydrocarbon exploration in this region has mainly been limited by poor subsurface imaging. Spectrum sought to address this issue through a new seismic acquisition programme, planned through the analysis of data from previous exploration campaigns. This allowed for a better understanding of the geological and geophysical complexities behind the seismic imaging challenges. Survey specifications and historical wells were made available from the DGH, the latter resulting in an essential source of information used to build and refine the velocity for both time and depth imaging.

The pre-acquisition study anticipated three main imaging problems: 1) strong velocity contrasts in shallow carbonates (single and interbedded multiples); 2) presence of salt bodies (complex ray path and edge effects (Jones and Davidson, 2014); and 3) small contrasts of acoustic impedance in the subsalt units (reduced signal-to-noise ratio). To optimize the acquisition parameters, the operational requirements were accurately tested to obtain a good control on energy recovered, in order to penetrate below the salt, in the syn-rift section (Esestime et al., 2017).

A 3D velocity model was adopted to understand ray paths and illumination under different variables: 1) several geometries

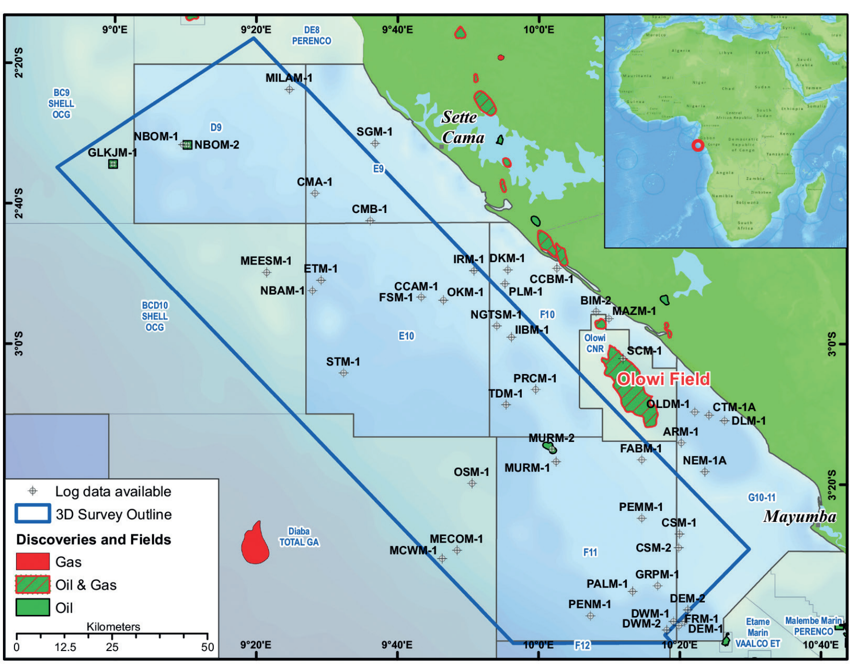

Figure 1 Map showing the new 3D seismic campaign conducted by Spectrum Geo Ltd in the shallow offshore Gabon in 2016- 2017.

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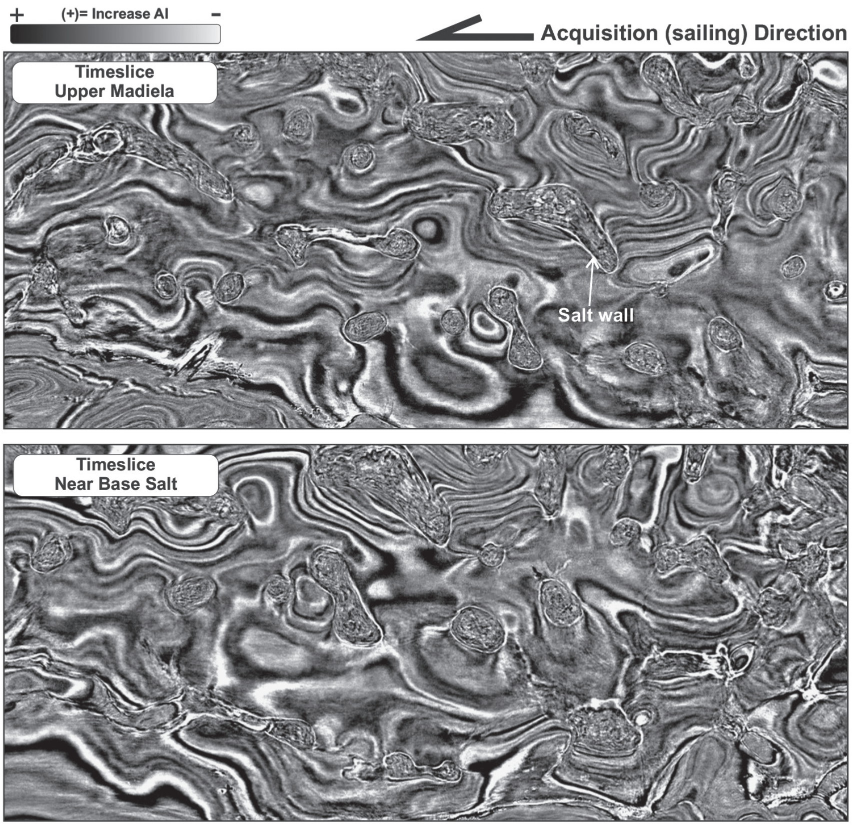

Figure 2 PSTM time slices showing the salt bodies and the surrounding carbonate pods. Note the soft event at the salt wall, as result of the higher velocity of carbonate respect to the salt.

and orientations of the salt bodies, 2) recurrent dips and strike directions in the sub-salt structures. The study proved that a sailing direction almost parallel to the coast was the most efficient for both operation and imaging purposes. In fact, primary energy from the sub-salt emerged since the single cable-shot stacks made on board the vessel, and the salt flanks were well defined by the initial migration tests (Figure 2).

The data were collected with two vessels; both provided with 8km-long offset streamers, with 15 seconds record length and continuous recording. The nearshore configuration had six streamers, while the deeper areas were covered using 12 streamers. Nominal shot spacing is 25 m in a flip-flop manner, with receivers every 12.5 m and cables 100 m apart. Water depths vary from 30 m to almost 1000 m, with more than 50% of the survey acquired in water depths of less than 100 m.

The most recent advances in seismic processing have been applied to enhance the modern broadband imaging techniques. Geological inputs have been used to carefully evaluate the geophysical outputs at all stages.

Further on we describe the processing methodologies and the main steps undertaken to create a velocity model for time and depth images. The imaging approach was made consistent with the geological complexities, honouring the geophysical observations made during the several steps of velocity analysis.

Geology and hydrocarbon prospectivity above and below the salt

The commonly held model for deposition of prospective sequences in South Gabon can be briefly summarized: the earliest Cretaceous extensional rifting sequence deposited fluvial-lacustrine sands (the Kissenda Formation) and shales in rift and lakes which periodically became anoxic preserving organic materials in the Kissenda and Melania source rocks (Teisserenc and Villemin, 1989). The syn-rift package has an internal stratigraphic fabric, with several intra-formational sands interbedded with fine-grained deposits, creating a characteristic setting with several targets and a number of potential pay-zones. Trapping mechanisms can be generated from stratigraphic termination, but the most common traps are on the numerous tilted fault blocks related to the rift (Figure 3a).

In the upper syn-rift, more fluvial deltaic sands were deposited – Dentale Formation – before a stage of inversion uplifted the very near shore rift, and post-rift transgression eroded the syn-rift to an almost planar surface across the area.

The syn- to post-rift transition is marked by major unconformities. Regional erosion truncated the topography of the rift, reducing the structural relief previously developed. It is on to this planar surface that the transgressive shore face sand, the Gamba Sands, were deposited, preserving an extraordinary reservoir quality, often several Darcy of permeability. This sand has usually been encountered in a fairly uniform 30-40 m thick package in the near shore area, though it has been reportedly thickened to more than 200 m in deeper water wells (Leopard-1). Even when it has been suspected that the Gamba could thicken within shallow water acreage, it had not been possible to observe this owing to limitations on pre-salt imaging. However, on the new 3D image the Gamba sequence seems to thicken and thin in some areas, yielding extra volume potential and even stratigraphic traps. Transgression continued after Gamba sand deposition and the Vembo Shale, an organic rich regional seal, was deposited. It is believed by some that this shale could be the main sealing unit for some of the pre-salt discoveries made within the Gamba sandstone.

Outboard of a structural high, a mid-ocean ridge developed below sea level, starting Atlantic drift. Inboard, a semi-isolated basin became an evaporating basin depositing the Ezanga Evaporites in the Late Aptian (Brownfield and Charpentier, 2006).

After this, a shallow water carbonate platform (Madiela Formation) built out over the salt, loading and deforming it into pillows (Figure 3a). Porosity and reservoir potential is generally located at the platform margin edge which is continually moving, responding to the loading of the salt. High-quality 3D seismic data is required to map this unit and look for plays associated with oil migration from the pre-salt. Several wells in the Gryphon area have hydrocarbon shows in the Madiela Fm. limestone suggesting that this play could have high potential. Thick sediment pods sink into the salt and the depocentre moves to and fro across the area.

The thick Madiela pods may become positive features – turtle backs. If they contain porosity and can be sourced, they may provide high-quality post-salt targets. At the same time, changes to global sea levels, brought clastic systems across the shelf changing the sediments from carbonate to clastic, as salt continued to move, dissolve and deform. Finally, the shelf became dominated by clastic systems (Cap Lopez Fm.) some of which are sandy and represent additional post-salt plays provided they can be charged from pre-salt source kitchens. Finding migration systems where the regional seal – the Vembo Shale – is thin or absent are potentially key to this play. In some areas, such as in the northwestern portion of the survey, post-salt overburden may be thick enough to allow some of the post-salt source rocks to be mature for oil, allowing the Madiela to be locally charged and reducing the risk of migration from pre-salt source rocks.

Time and depth imaging

The survey size required a high standard of computational power to execute the processing sequence in a flexible and interactive manner. Spectrum awarded this work to DownUnder GeoSolutions (DUG), immediately establishing a synergy between the management and technical parts of both companies.

Time processing followed standard steps in initial de-noising, applied as time frequency de-noise (TFDN), in the shot domain,

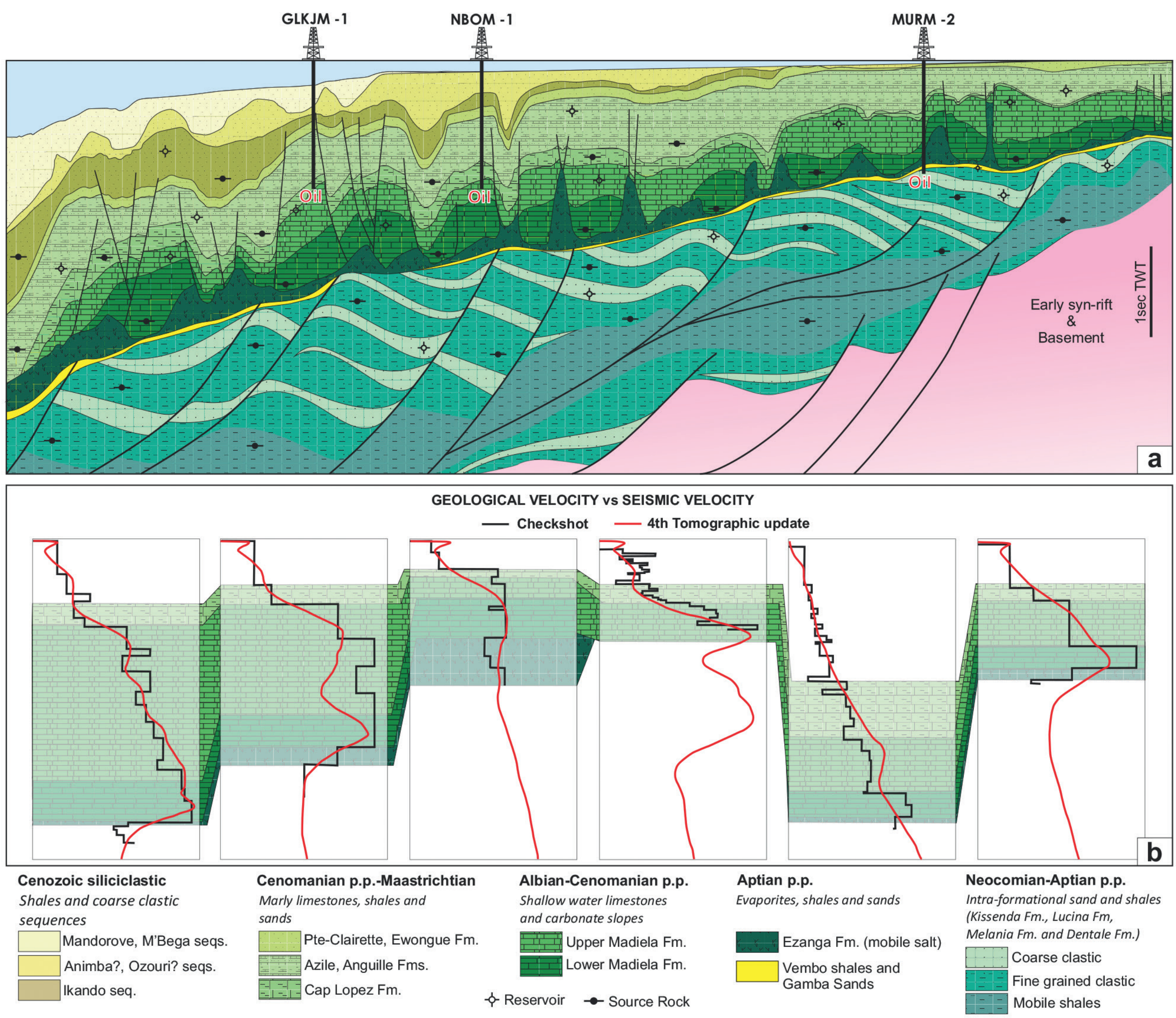

Figure 3 a) Geological sketch and petroleum systems of the main pre- and post- salt hydrocarbon plays. b) Correlation panel between well checkshot velocities and seismic velocities obtained from the tomographic update of an unconstrained isotropic model.

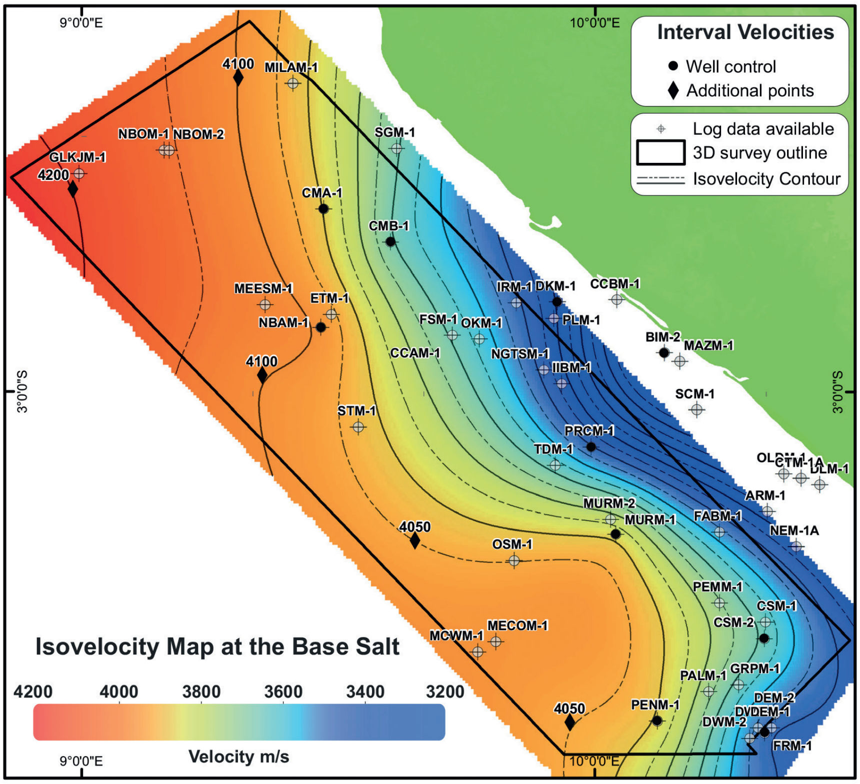

Figure 4 Isovelocity Map (Vo): applied to the base salt to generate for the subsalt velocity gradient.

which removed swell noise. Low-frequency random noise is further attenuated via Cadzow filtering in the shot domain, creating a noise model and subtracting it from the input data. Direct arrival attenuation is achieved using an iterative plane wave decomposition to model the input and subtract linear noise from the data De-ghosting technology allows us to remove the amplitude and phase distortions caused by both source and receive ghosts. The process effectively de-ghosted offsets and dips, broadening the spectrum above the salt as well in the deep section. In this case receiver de-ghosting was performed first, followed by source de-ghosting.

De-ghosting was followed by signature deconvolution, incorporating de-bubble and zero phasing, to then start in the meticulous definition of the water bottom in the shallower areas <50m water depth.

Extensive testing was performed on a series of sail lines ranging in water depths from very shallow to the deepest in the survey area. A multi-pass approach to de-multiple was adopted, based on 3D SRME, 3D shallow water (SWSRME) and 2D shallow water de-multiple (SWD). A cascaded approach to the adaptive subtraction, where each model is computed using an input based on the results of the previous application, gave better results than the simultaneous approach. The sequence is differentiated between the outboard and the inboard areas, with 3D SWSRME and SWD preceding any 3D-SRME in the inboard data, but applied after 3DSRME in the outboard area.

After de-multiple, the section above the salt was already clearly visible, to be confidently picked in migrated and unmigrated data, to finally start the interpretation for the velocity model building.

Further demultiple and noise attenuation was applied before Anisotropic Kirchhoff PreSTM.

Geological constraints in terms of well velocities were incorporated into the velocity model building workflow in the early stages as a starting model for tomography. A gradient velocity function was used from base salt.

Post-migration processing included further passes of de-noise and de-multiple. RMO was run at 200 x 200 m intervals and a final velocity update was performed using time tomography.

The velocity modelling workflow started almost conjunctively in time and depth processing, creating a joint exercise for testing the migration and to reconsider more advanced demultiple and gather conditioning. However, the effort for the PSTM (Pre-Stack Time Migration) velocity was soon overtaken by the PSDM (Pre Stack Depth Migration) velocity field.

Velocity flood vs tomography

Several seismic markers are well imaged above the salt, such as the main Tertiary unconformities, the Cap Lopez and the Madiela Formations. This enabled the geophysicist to pick a reliable move out corrections (NMO and RMO) since the rawest data was made available. As a result, interval velocities obtained were geometrically consistent with the horizons and had similar ranges to the well check shots, despite limited vertical and lateral resolution.

Below the salt, the presence of visible primary energy initially encouraged the geophysicist to pick on gathers, but the resulting field was proven not to be reliable as it was not able to identify the velocity inversion known to exist at the base of the salt (Figure 4).

Well data shows seismic velocities of 4500-6000 m/s for the Madiela Carbonate and approximately 4400 m/s for the

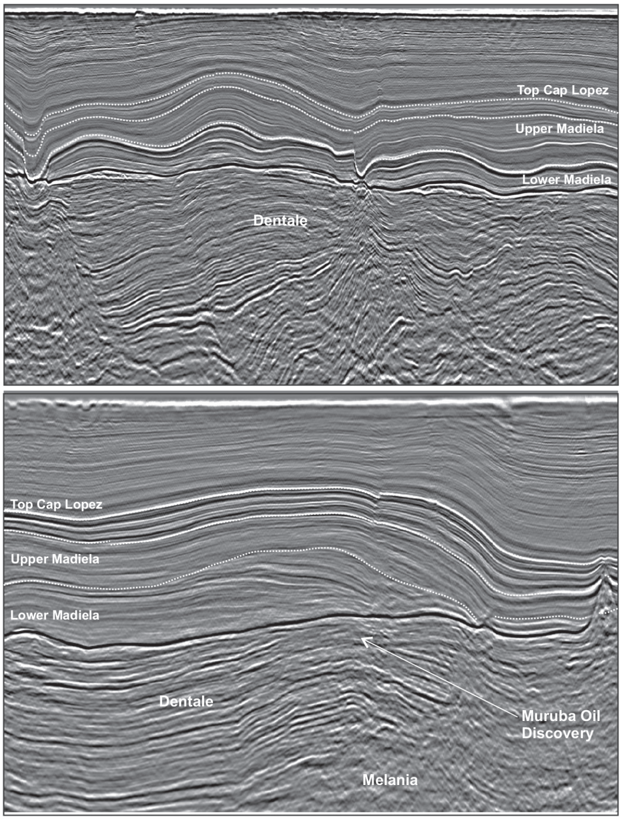

Figure 5 PSTM sections showing the pre and post salt- targets.

Ezanga Evaporites. Below the salt, the velocity drops to less then 4200 m/s (Jones and Davison, 2014).

To separate unequivocally the carbonate and salt velocities from the subsalt, a simple gradient function perpendicular to the base salt itself was generated and flooded from the base salt down. The trend was remarkably linear, despite minor variations in interval velocity through different thicknesses. The gradient function is an average of the interval velocities taken at different depths in the subsalt units. The function was created as a time-incremental velocity and clipped at the maximum value of 6500 m/s

$$V\left(S_{twt}\right) = V_0 + 900\frac{m}{s^2} * s$$

The gradient function was complemented with the lateral variation of the starting velocity (Vo) at the base of salt (Figure 4). This was calculated an isovelocity grid extracted on an interval of 100-150m below base salt (Figure 4). The velocity model gave immediate and effective uplift when used as stacking velocity in the subsalt, and it was used to initially flood the migration velocities for both time and depth migrations. The subsalt gradient was updated through reflection tomography as the depth imaging progressed (Kirchhoff PSDM), instead, only a smoothing operator was applied for the time migration.

The resulting wells database is excellent for testing the velocity field during all the tomographic updates, especially within the Madiela carbonate and the salt. Carbonate and salt geobodies were flooded using velocity functions extracted from sonic and checkshot data, then updated through tomography; meanwhile a completely unconstrained model underwent a number of updates. This exercise was continued until the velocity field of the unconstrained model became horizon consistent with the Madiela and Cap Lopez Formations, and matched the well data better than the flooded model (Figure 3b). Anisotropy was also considered, for minor refinements of the well-to-seismic tie in depth. Horizons and geobodies were used only as ‘soft boundary’ constrains, to confine the tomography, or to clip the leakage of high velocities (Lower Madiela 4500-6000 m/s) into slower salt bodies.

This approach was very effective in cases where the salt withdrawal created a weld between the Madiela carbonate and the syn rift. The imaging was achieved during the intermediate stages of the PSTM and after the initial tomographic updates for the PSDM. The energy emerged from the syn rift, allowing picking of the Residual Move Out and refining the velocity gradient. By then, the velocity model was ready to be refined in

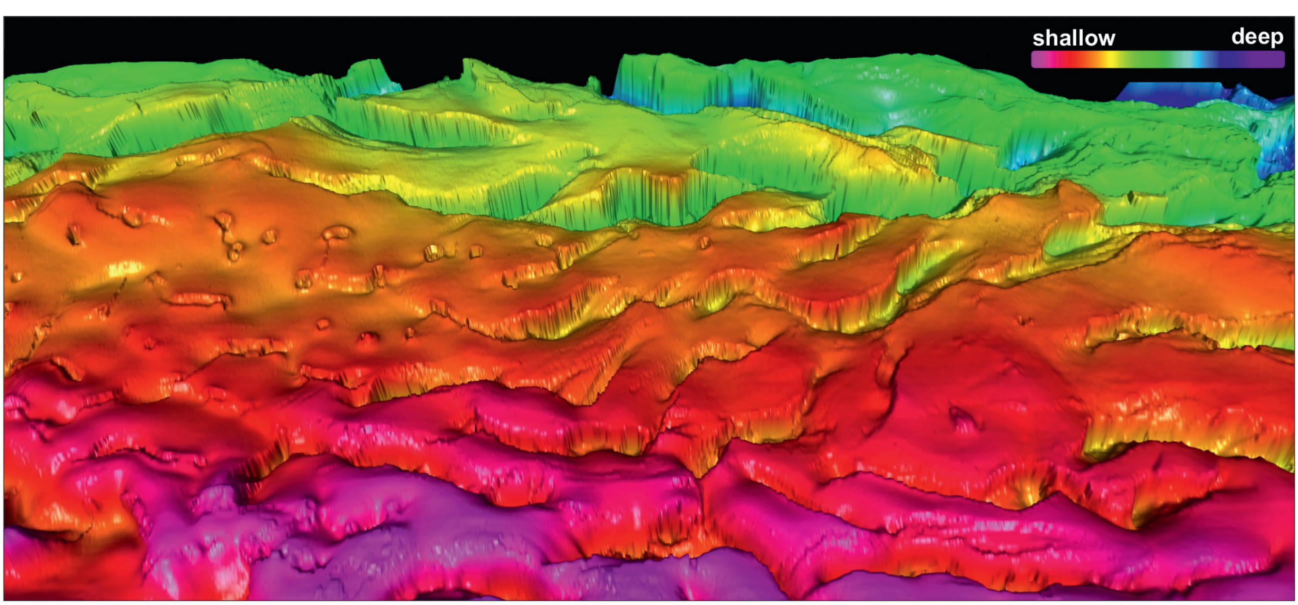

Figure 6 TWT horizon at the Top Cap Lopez. Note the number of structural closures and the prospects potentially generated in the post-salt.

the noisy areas underneath the salt. Additional velocity analysis has been conducted in the salt bodies, comparing different top salt scenarios, in order to recover the energy at the base salt and to reduce the distortion at the edges of the salt bodies. With the final update, the velocity field was finally suitable for more advanced depth imaging through Reverse Time Migration.

New 3D prospectivity

Even at the early PSTM processing stage, the results have already revealed unprecedented pre-salt imaging, allowing a better understanding of the wells drilled, such as the Muruba discovery made in a sequence 400 m below the Gamba sandstone, which until now had not been fully understood. The final PSTM shows the structure and sequence associated with this discovery (Figure 5) and proves that the intra-Dentale tilted fault blocks are a valid play type. Away from the Muruba Discovery we identify similar, and even larger, undrilled intra-Dentale structures which had not been seen before. The more traditional Gamba sandstone play is also observed for the first time to thicken in places, providing the potential for both structural and stratigraphic traps associated with this very prospective sandstone. One of the biggest surprises is the very large undrilled post-salt Madiela structures (Figure 6) which are supported by nearby wells with hydrocarbon shows.

Conclusions

Multi-disciplinary integration from pre-acquisition modelling, adequate acquisition parameter design, successful operations management and a very careful processing methodology, fully integrated with well and horizon interpretation data, are resulting in the identification of unrevealed potential in the shallow water of Southern Gabon.

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