

3D shallow water seismic survey planning to deliver sub-salt imaging in South Gabon

Paolo Esestime¹, Laura Arti¹, Milos Cvetkovic¹, Karyna Rodriguez¹ and Neil Hodgson¹ describe a pre-acquisition study to address sub-salt imaging challenges and to optimize the survey design.

Introduction

The shallow offshore in south Gabon has been explored for more than 50 years, highlighting the potential for oil discoveries. However, exploration of the sub-salt syn-rift section requires an advanced support that only modern, regionally consistent 3D seismic data can provide. Such support was the objective of a large-scale multi-client 3D seismic programme, representing a collaboration between Spectrum Geo Ltd and the Gabonese Hydrocarbon Authorities (Direction Generale des Hydrocarbures (DHG)), which commenced in December 2016. This survey acquired 11,500 km² of 3D seismic data in the 'Gryphon Area' – the shallow offshore of Mayumba and Sette Cama, west of the Olowi Field, in a range of water depths from 20 to 1000 m (Figure 1).

Advanced and accurate modelling allowed for the survey specifications to be tailored to the geological setting and the exploration targets. The previous geological and geophysical exploration was taken as background information to develop the new subsurface imaging.

For many years the accepted exploration target in South Gabon has been the high-quality transgressive Gamba Sand-

stone of Lower Aptian age, located just below the Ezanga Salt Fm. As the base of the salt is separated from the near ubiquitous Gamba Sandstone Fm. by thin shale (Vembo shale member) the main challenge for seismic acquisition therefore has been the accurate imaging of the base salt, and more importantly the accurate depth imaging of this unit. The overburden is complicated by heterogeneous and highly variable velocities in the post-salt carbonate of Madiela Fm., complex geometries of top salt and variable compositions and velocities within the salt.

In south-west Congo (Brazzaville), a number of discoveries have been made over the past 4-5 years, in a new intra syn-rift play. This play targets the Djeno Fm., equivalent in age to the lower syn-rift Kissenda Fm. of South Gabon. This play has rarely been targeted in Gabon owing to the poor imaging of the pre-salt section on legacy 2D and 3D data.

This article describes the methodology applied to the pre-acquisition study, which guided the acquisition operation and gave a preliminary insight of the challenges to be faced during the processing.

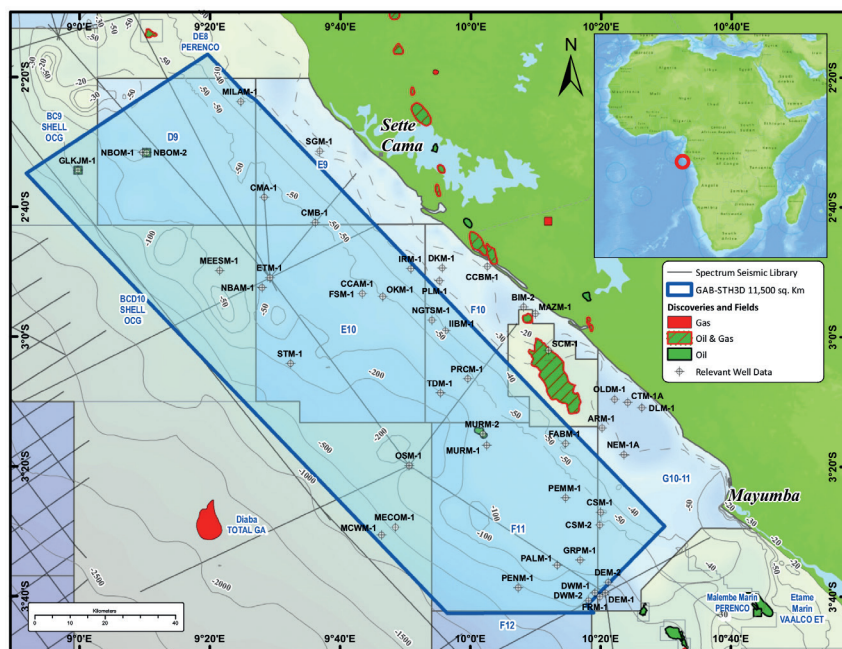


Figure 1 Map showing the new 3D seismic campaign conducted in the shallow offshore Gabon in 2016-2017 from Spectrum Geo Ltd.

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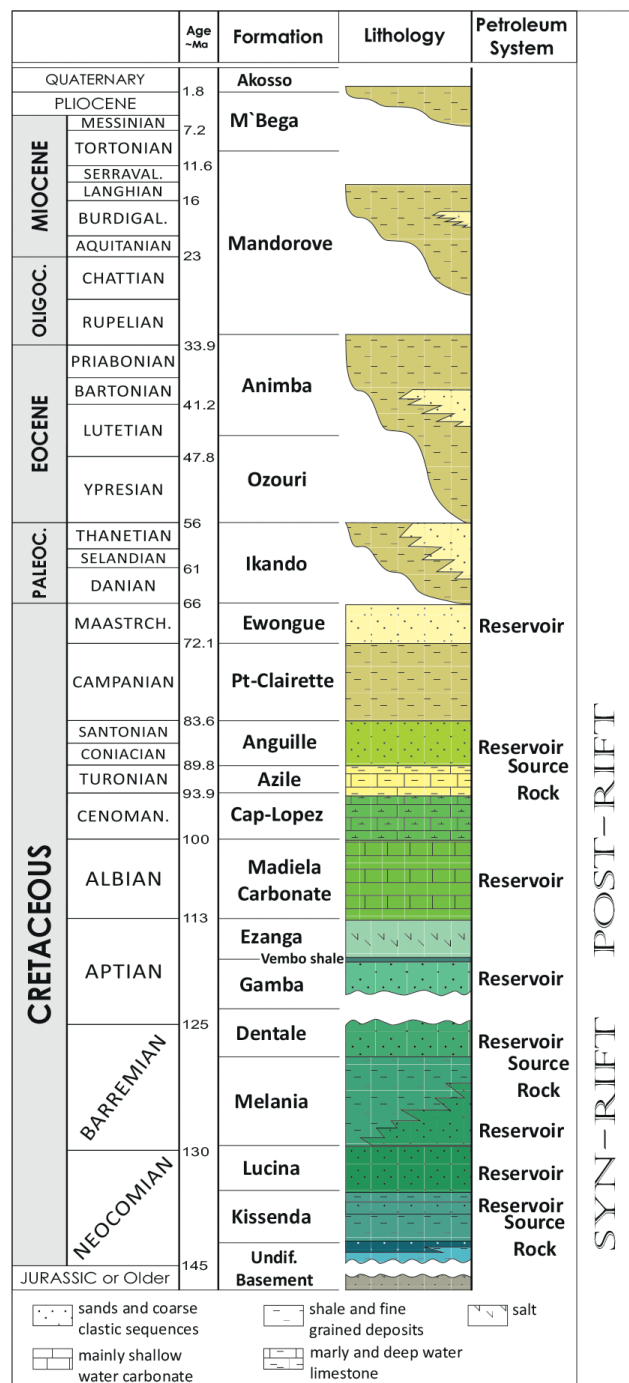


Figure 2 Schematic stratigraphic section representative of the shallow offshore areas in South Gabon.

Geological setting and exploration targets

The pre-salt section in the shallow water of South Gabon is underlain by rifted continental crust, comprising a basal metamorphic basement, and a syn-rift section comprising sub-aerial sediments deposited in a fluvial deltaic environment (Figure 2).

Syn-rift sediments can be subdivided into an Early syn-rift (Lucina/Kissenda Fms.) section and Late syn-rift (Dentale Fm.) sequences. While both were deposited during the rift event that separated African Gondwana from South American Gondwana, the two sequences may be distinct such that they are separated by an unconformity, which created two distinct hydrocarbon

systems. In this case the 'intra syn-rift play' targeted coarse clastic inputs in the Kissenda Fm., charged from Kissenda Source Rock at the base below and Melania shales above (Figure 2). The Melania Fm. itself appears disconformable with the Kissenda Fm., in onlap relationships with lower structures, and potentially provides top seal to the lower syn-rift play.

At the end of the dominantly sub-aerial syn-rift, continued subsidence enabled a marine transgression which eroded and peneplained the existing morphology, and deposited a transgressive shore-face sandstone – the Gamba sandstone. This may vary in thickness across the relict topographic highs, providing stratigraphic termination and pinch out. As facies belts moved eastwards over what is now onshore Gabon, the distal equivalent of the onshore Gamba Sands were deposited (Vembo Shale), potentially providing a regional seal to the Gamba reservoir. In fact, in places the Vembo shale represents a restricted deposit, rich in organic material that may represent an additional source rock.

Where the Dentale sequences sub-crop the high permeability Gamba sands structural closure above the Gamba sands needs to be sealed by the Vembo shales or the Ezanga evaporites to create an efficient mechanism for trapping. For example, in the Etame Field oil is retained in a Dentale reservoir within the structural closure present at the Gamba level. Elsewhere, where Dentale is truncated by faults, intra Dentale traps can be generated by cross fault seal (N/G and fault smear dependent), and in stratigraphic closures created by a facies variation. A coarse-grained sequences may also be controlled by fault activity and regional trends in the syn-rift structures.

Velocity modelling

The modelling of the seismic interval velocity field (P-wave velocity) was the most crucial point to optimise the design and processing of the new 3D seismic acquisition. The velocity field was shaped to be a robust expression of the geological setting and its complexities, regionally representative across a distance of 300 km along the coast and more than 100 km in deep outboard.

For input data to the acquisition model, only limited well control was available, and the most representative velocity values were taken from the well Tiya-1, which ties the available 2D seismic vintages, regionally extended across the entire Gabonese shelf. This allowed for the extrapolation laterally through the most relevant seismic stratigraphic sequences. To populate the model with more refined details of salt and carbonate structures, a number of horizons were extracted from existing 3D seismic in the area of Gryphon South, offshore Mayumba (Figure 1). Initial indicative horizons were created during several sessions in the data room provided at the DGH's offices in Libreville (*Direction Generale des Hydrocarbures*). The main focus of this work was at the Top Salt horizon and 'Top Carbonate' (formally Cap Lopez Fm. in Figure 2), to identify plausible trends and geometries generated during the salt movement.

The structural model produced by this initial work was relatively simple, with a minimal control of the halokinesis on the carbonate sedimentation, allowing seismic facies, to be correlated hundreds of kilometres across the area. Large carbonate turtles and cuvete are generated mainly after deposition, and are similar to those identified in the deep offshore (Duval and Firth, 2015). Salt overhangs are extremely localized or not present, and salt

bodies are mainly confined in thin diapirs in isolated locations or organized along scattered NNW trends, associated to lateral withdrawal of the evaporites.

The model was then used to calculate ray tracing solutions, under different azimuths and offsets. Several acquisition designs were evaluated, constrained by the close proximity of the coast and established infrastructure. Modelling was focused on evaluating the impact of the sailing direction (inline direction) on the signal recoverable below the salt and the carbonate.

The final structural velocity model was created out of ten layers, from the seafloor to three subsalt targets located respectively at a depth compatible with the Dentale Fms. and the deep units of the syn-rift (Figure 3).

To test the reliability of the ray-tracing model, those factors having negative impact on the sub-salt illumination were exaggerated. Salt velocity was increased by 20-25%, salt thickness slightly increased and carbonate architecture subdivided into two layers of Madiela Carbonate, consistent with regional observations. Structural dips in the subsalt targets were assumed to be oriented parallel to the coastline, to amplify potential issues derived from a coast parallel sailing direction.

The velocity within the intervals was assumed to be consistent with the well Tiya-1; velocity gradients 'G' have been inserted within each layer to account for density variations, compaction and burial trends, (Figure 3): Seawater 1500 m/s; Miocene-Qt. 2000 m/s, $G=0.6$; Early Tertiary-Late Cretaceous 2150 m/s, $G=0.8$; Cap Lopez-Madiela Carbonate Fms. 4200 m/s,

$G=0.1$; Lower Madiela Carbonate 4900 m/s, $G=0.1$; Evaporites 'Ezanga Fm.' 5300 m/s $G=0.1$; Base Salt 4000 m/s $G=0.1$; Subsalt Target 1 4250 m/s, $G=0.1$; Subsalt Target 2 4600 m/s, $G=0.1$; Subsalt Target 3 or Basal Layer 5500 m/s, $G=0.1$.

Seismic modelling and illumination issues

We followed a modelling approach for seismic stacks based on an efficient numerical workflow, which creates statistical ray parts solutions to evaluate the 3D illumination at defined targets (Cvetkovic et al., 2014).

Combined 3D and 2D finite difference modelling, with ray-tracing based attributes, allow us to quickly turn around a robust analysis of different scenarios or models from the acquisition to optimize the ranges of maximum offsets, near offsets, record lengths, source and receiver sampling.

Raytracing-based attributes have been extracted at the subsalt targets, to analyse the impact of the overburden units in the recovery of the signals reflected from the subsalt. Ray-paths recovery and failures were both present under several directions of illumination, both parallel and perpendicular to the coastline. Small improvements were observed for cable lengths above 7000 m offset, and 8000-m streamers were used in this acquisition.

Both salt bodies and carbonates acted as diffraction levels owing to the velocity inversion below the salt. A good amount of the energy was seen to reach the subsalt targets, even around salt bodies and under different directions, to be eventually lost on its way back to the surface. In fact steep reflectors in the subsalt, created a ray-path problem which cannot be completely solved by changing shooting directions. This supported the selection of NW-SE (coast parallel) to ensure the best efficiency for the operation.

The illumination model has been complemented by the generation of amplitude sections in inline and crossline directions selected where the illumination was showing the most critical results.

Starting with modelling and migration in 2D, we tested a number of parameters to reduce the number of scenarios to undergo more time consuming 3D modelling. As 2D acoustic FD on modern computing systems can run within minutes, we simulate multiple variations of surface marine geometries with different operational settings, to understand maximum offsets, lack of near offsets, source and receiver sampling and record lengths. Combinations of simultaneous shooting and continuous recording have also been simulated to test suitable regularization/interpolation and de-blending algorithms.

In order to get more realistic shot records we add random and coherent noise trains, and generate synthetic shot records with stronger amplitude of water bottom multiples with acoustic modelling algorithms by using a free surface boundary condition and exaggerated acoustic impedance by introducing higher velocities right below the water bottom layer. Each set of synthetic shot-gathers were migrated using Reverse Time Migration (RTM), as an uncompromised imaging algorithm that will honour steep dips and complex overturned structures.

Figure 4 shows RTM 25 Hz stack along inline and line using a previously described model with 7000 m offset, 25 shot spacing,

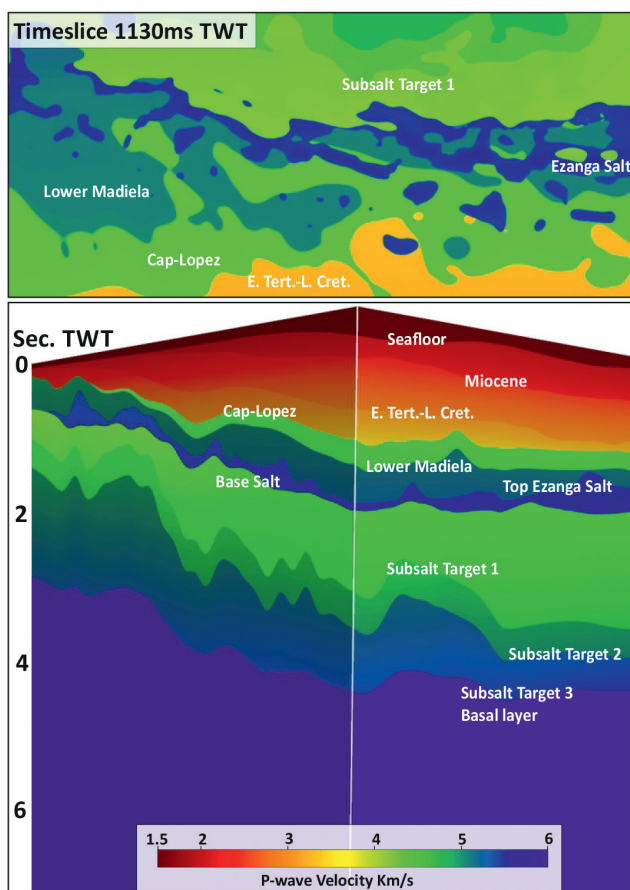


Figure 3 3D Model of the Seismic Interval Velocity Field (P-wave), developed for the pre-acquisition study.

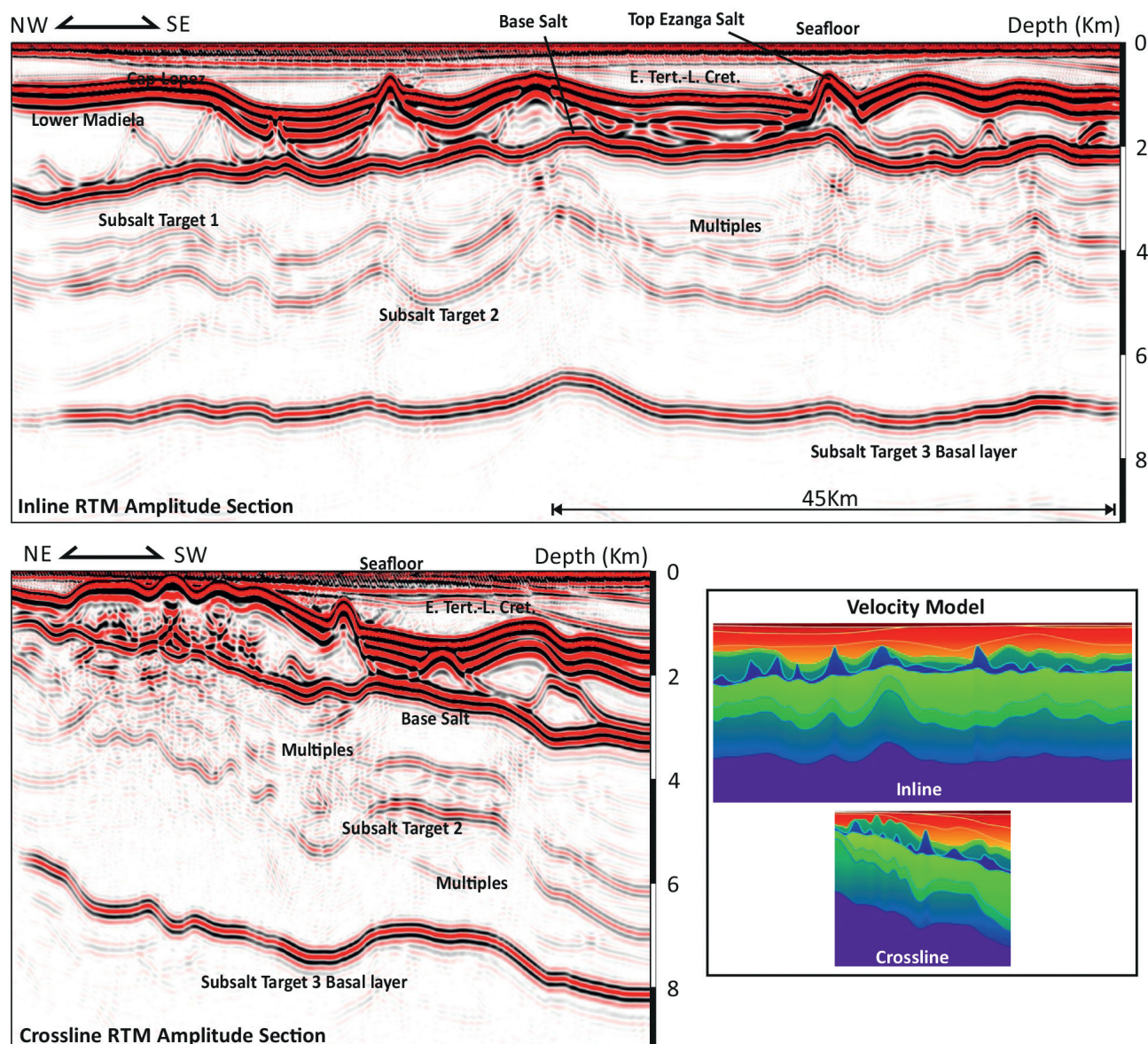


Figure 4 Forward modelling of Reverse Time Migration stacks along inline and crossline directions generated from the velocity model (sections in the box). 7000 m offset (cable length), 25 m shot spacing, 12.5 m receiver spacing and 10s of record length.

12.5 receiver spacing and 10s record length, without continuous recording. With this set-up we image base of salt as well as two pre-salt target horizons reasonably well. The subsalt targets were always present along the section, while dimming in amplitudes, for losing energy in the steepest sectors. Once again, energy recovery was compared under different offsets, which confirmed not remarkable differences by using offset longer than 7000 m.

RTM testing anticipates the challenges expected at processing stages of the new data. Events related to multiples are generated along the enormous velocity contrasts at the carbonate and salt levels, reaching amplitude values comparable with those forming the subsalt targets (Figure 4). Actually the velocity and density analysis conducted on the well Tiya-1 suggested that low contrasts in acoustic impedance could be expected for the subsalt layers, creating dim primary amplitudes interfering with the multiple generated in the overburden sections.

To examine cable and receiver separation we introduced a stratigraphic model. We generated an arbitrary velocity log

curve and imposed a velocity variation on a predefined velocity trend guided by three regional horizons. Such a model will have vertical and lateral resolution that will support fine scale features and higher frequency modelling and migration. We use 70Hz maximum frequency for both modelling and migration. To simulate cable separation we use shot spacing in 2D and analyse RTM images as well as depth migrated image gathers. Spacing larger than 100 m creates more alias imaging of shallow sections, compromising the near offsets and increasing unwelcome noise.

Operational goals

The survey extends for approximately 11,500 km², in water depths between 20 m to 1000 m (Figure 1). The area is elongated parallel to the coast, for approximately 180 km in a NW-SE direction, extending in the outboard offshore for 60 km. Both open acreage and licences have been covered, and reached to within a few kilometres of the production facilities of the Olowi Field (Figure 1).

Given the proximity of the Gabonese coastline, shallow water depths and existing infrastructures, as well as heavy fishing activity, the azimuth survey was optimized for operational challenges and to address imaging issues. The impact of the sailing direction was the most crucial parameter to be addressed, and it has been the main focus for the velocity modelling and the related illumination study. A sailing direction of NW-SE was proven to be suitable for any subsalt targets, included for deep events at 7-9 sec TWT, below the exploration targets. The imaging of the salt geobodies was only minimally impacted by the use of trends of the salt-related structures and the shallower geology.

The objective of the survey was to resolve the sub-salt imaging. However, an efficient operation, performed in a timely and safe manner in an operationally challenging area, is an also essential planning consideration. The optimal survey design has proven to be simple: tow a conventional horizontal streamer spread with a relatively deep tow, long offset streamer configuration and optimally source output necessary to image in the sub-salt section to ensure the range of frequencies necessary for targeting the imaging objectives.

Primary energy was clearly imaged below the salt during the acquisition phase and visible on the 2D brute stack sections produced from single cables, immediately on board and with very minimal or no preliminary processing applied.

The seismic survey was acquired in seven months by two separate vessels: one operating in shallow water depths ranging from 28 m to 50 m towing a spread of six streamers with 8-km streamer length separated by 100 m. This configuration was maintained for approximately 2500 km² with and one vessel acquiring in water depths ranging from 50 m to 800 m towing a spread of 12 streamers with 8-km streamer length at 100 m separation covering an area of approximately 9000 km².

The streamer tow depth of 17 m was achieved by both vessels and enabled recording to the very low frequencies required for sub-salt imaging, allowing for optimal broadband processing and to enhance potential low-frequency seismic facies in the pre-salt units.

Ultimately, the combined sailing of two vessels was planned in such a way that seismic interference was avoided without affecting the efficiency of the survey operation.

Conclusions

The Spectrum survey planning in south Gabon was specifically designed for imaging the Dentale and Kissenda syn-rift targets (Figure 2). This allows future exploration to develop the emerging sub-salt oil-play, currently unrevealed in South Gabon.

The survey planning was based on an accurate analysis of the geological setting, both at regional and prospect scales, to generate a robust velocity modelling for subsurface illumination analysis (Figure 3).

The illumination study suggested how seismic energy can penetrate, and be recovered, from below the salt bodies and the Madiela Carbonates, addressing the most effective and operationally efficient geometry of acquisition. Forward modelling of amplitude sections (Figure 4), both for inline and crossline directions, was able to reproduce the imaging issues observed in pre-existing 2D and 3D seismic surveys, giving a valuable insight into the challenges to be faced during the processing phase.

Acknowledgements

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