Simultaneous long offset (SLO) towed streamer seismic acquisition

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SUMMARY

An innovative 3D towed streamer project in offshore Gabon used a dual-vessel continuous long offset streamer configuration to acquire 0-12 km offsets with ten dual-sensor streamers. Streamer control for the 6 km streamers was robust and avoided operational complications or logistical penalties. Simultaneous shooting maximized inline shot density for long record lengths, thus capturing unaliased deep target reflections from rugose base-salt and sub-salt horizons. Survey design benefited from prior 2D survey experiences with a variety of broadband source and streamer technologies, and the use of 2D streamers as long as 12 km. 3D illumination modelling further suggested that offsets as long as 16 km could be expected to yield useful base-salt and sub-salt reflections.

Wavefield separation processing yielded full receiver-side deghosting onboard, followed by an inversion-based separation of simultaneous shots onshore. The ultra-long 12 km offsets combined with strong amplitudes of deghosted low frequencies have yielded encouraging sub-salt and pre-salt imaging.

Key words: long offsets, simultaneous shooting, dual-sensor streamer, wavefield separation, illumination, sub-salt, pre-salt, Gabon.

INTRODUCTION

A 3D seismic survey commissioned by Ophir Energy Plc and Petrobras in offshore Gabon during early-2012 is located in water depths of about 400-1200 m, along the eastern flanks of the Mbeli and Ntsina exploration blocks (Figure 1). Previous 2D dual-sensor acquisition and processing in the survey area has demonstrated the benefits of wavefield separation for imaging the complex top and base salt morphology and sub-salt structures, but out-of-plane reflections rendered the overall result quite unsatisfactory. Similar challenges were observed with 2D field testing with a deep-towed 12 km continuous hydrophone-only streamer and a deep-towed de-tuned source array, but improved sub-salt structural and stratigraphic imaging encouraged the use of very long offsets (Fontana et al., 2011).

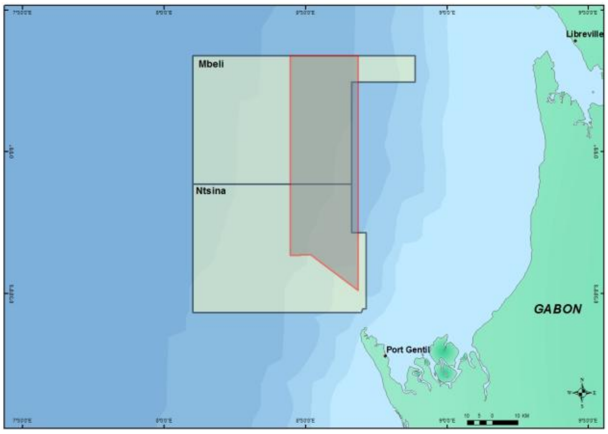

Figure 1. Location map for the Stenella 3D survey in offshore Gabon.

Exploration has recently focused on deep water channels/canyons and sub-salt targets, each analogues to proven petroleum systems in Brazil. No pre-rift sediments are present in the North or South Gabon Basins where basin fill sediments directly overlie Pre-Cambrian basement. Initial rifting formed a series of asymmetric horst-graben basins which trend parallel to the present-day coastline. Thick sequences of fluvial and lacustrine sediments were deposited in these rift basins, with the lacustrine rocks forming important source rocks. Subsequent basin-wide normal faulting resulted in increased syntectonic lacustrine sedimentation. Post-rift sediments range from Aptian to Holocene in age and represent the initial opening of the Atlantic in equatorial West Africa. The initial post-rift rocks are of early to Mid-Aptian age and consist of continental, fluvial and lagonal sediments deposited as rifting ceased. A period of extensive deposition of evaporite units then followed. A major unconformity caused by a global eustatic sea level drop during the Eocene-Oligocene caused nondeposition and erosion along the slope and basin. Sediments were carried down canyons 300-500 m deep cut into the platform and shelf. All channels are perpendicular to the slope, and some contain sand formed as basal lobes. Turbidites may exist in the (unexplored) deep offshore areas, but are not established. Overall, a variety of geological features and play types were thought likely to exist but were unverified in the survey area. The explicit use of ultra-long offsets acquired in a 3D survey was viewed was the best platform for sub-salt and pre-salt imaging, combined with broadband seismic processing and imaging.

SURVEY DESIGN

3D ray tracing-based illumination modelling was pursued with a 3D model built from the inversion of marine gravity gradiometry data. Offsets up to 16 km were recorded from base-salt horizons, encouraging the belief that 3D acquisition with 12 km streamers would provide the optimal platform for base-salt and sub-salt seismic depth imaging. This presented an operational dilemma; however, as no wide-tow 3D streamer spread had historically ever been known to tow streamers longer than about 9 km.

Continuous long offset (CLO) acquisition combines a dual-vessel operation using only short streamers with a smart recording technique involving overlapping records (van Mastrigt et al., 2002). The dual-boat operation effectively doubles the streamer length, thus obtaining very long offset ranges. A compromise is that the effective inline shot spacing is doubled in comparison to single vessel operations. A revised configuration referred to as simultaneous long offset (SLO) acquisition was proposed here wherein simultaneous shooting of the forward and rear source vessels halved the inline (CLO) shot spacing. Recent advances in simultaneous shot separation allow the SLO configuration in Figure 2 to have the shot sampling, offset distribution and fold of a single vessel configuration with 11.8 km streamer length, but by using only 6 km streamers towed from the rear vessel. Obvious operational benefits are that survey infill and streamer feathering and handling challenges for 6 km streamers are vastly reduced in comparison to the (untried) scenario with 11.8 km streamers. Note that a 200 m "vessel overlap" is used to avoid coverage holes appearing in the mid offsets when feathering approached the maximum values anticipated for the operating conditions throughout the survey area. The acquisition configuration used was as follows:

- 10 x 6,000 m solid dual-sensor streamers towed at 15 m depth, 100 m streamer separation.
- Near offset of 100 m, 200 m vessel overlap, far offset of 11,800 m.
- 4,135 in^3 dual-source, 2000 psi, 25 m shot interval, 9 s record length, simultaneous shooting.

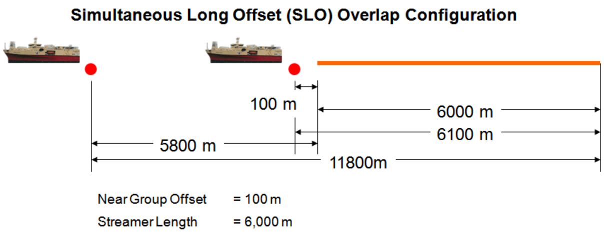

Figure 2. Schematic vessel configuration for SLO yielding maximum inline offset of 11.8 km.

Previous 2D dual-sensor acquisition and processing in the survey area had demonstrated the benefits of wavefield separation for imaging the complex top and base salt morphology and sub-salt structures, but out-of-plane reflections rendered the overall result quite unsatisfactory. Similar challenges were observed with the aforementioned tests with deep-towed conventional streamers with 12 km offsets. Several benefits were anticipated for 3D acquisition and processing of dual-sensor streamer data, including improved demultiple (e.g., Hegge et al., 2011), an optimal platform for high-end velocity model building (e.g., Kelly et al., 2010), and more robust reservoir characterization (e.g. Reiser, 2011). Emerging methods such as imaging with multiples (Whitmore et al., 2010) are also applicable to dual-sensor streamer data.

RESULTS

Dual-sensor streamers enable wavefield separation processing to isolate four wavefields: The up-going pressure and velocity wavefields, and the down-going pressure and velocity wavefields (Carlson et al., 2007). Key elements of the SLO dual-sensor processing flow were as follows:

- Swell noise attenuation and wavefield separation onboard.
- Optimized source separation (van Borselen et al., 2012).
- Phase-only Q compensation.
- Cascaded demultiple, including dual-sensor 3D SRME.
- 5D anti-alias anti-leakage Fourier regularization.
- Anisotropic Kirchhoff dense velocity model building.
- Detailed PGS dipscan and beam depth migration velocity model updates, including RMO, tomographic inversion and iterative salt flood
- Several depth imaging deliverables including PGS beam and Kirchhoff solutions.
- Post-imaging demultiple and processing

Figure 3 shows an initial brute stack test of simultaneous shot separation applied to 0-6 km offsets. Shot separation was robust for all water depths encountered.

Figure 4 shows 0-12 km CMP gathers built by combining the near and far offset contributions at each location. As observed on historical 2D seismic data, the strong sub-salt event at about 3.5 s TWT is obscured by strong noise trains beyond offsets of 3-4 km. The revelation here is that the event reappears at offsets beyond 7-8 km. Note than in practice the near and far offset ranges were processed as independent gathers.

Establishing the salt model morphology was a challenge in depth velocity model building. An integrated workflow that combines PGS beam migration and tomography in a visualization environment enabled rapid-cycle salt interpretation and velocity model updates. Figure 5 demonstrates the contribution of far (6-12 km) offsets to imaging sub-salt and pre-salt events. Several factors contribute to the dramatic improvements in the new data: Receiver-side deghosting (wavefield separation), a superior velocity model, the "dipscan" component of PGS beam pre-stack depth migration (PSDM) migration that avoids coherent noise contributions to imaging (Jiao et al., 2009), longer offsets, and the multi-pathing capability of beam migration to image steep dips.

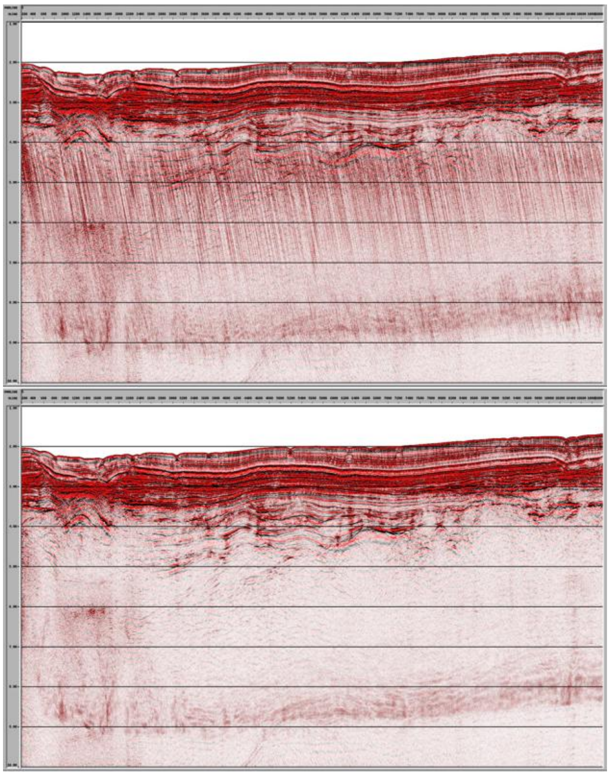

Figure 3. Brute stacks before (upper) and after (lower) separation of simultaneous shot gathers. The residual energy in the lower panel is primarily far offset noise that has not yet been muted off.

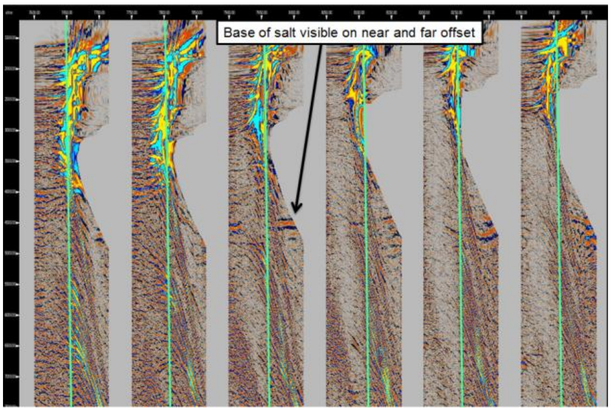

Figure 4. NMO corrected CMP gathers reconstructed for display from the near and far source contributions. The offset range displayed is 0 – 11.8 km, and the pale vertical line on each gather represents an offset of 6 km. Vertical scale is 0-6.5 s TWT.

DISCUSSION

The SLO concept presented here offers a wide variety of flexible 3D acquisition configurations. For example, at 25 m ultra-dense streamer separation it is typically impractical to tow streamers longer than 3-4 km. An SLO configuration could, however, record offsets of up to 8 km with 25 m streamer separation. Conversely, offsets up to 16 km can be acquired with conventional streamer separations of 100-150 m and 8 km streamer length. In all cases, shot interval for processing is uncompromised.

CONCLUSIONS

Dual-vessel simultaneous long offset (SLO) towed streamer acquisition uses simultaneous shooting to preserve inline shot density compared to single vessel shooting with half the maximum offset achieved. A 10 dual-sensor streamer SLO configuration efficiently achieved offsets of 0.1 to 11.8 km in offshore Gabon, yielding sub-salt and pre-salt imaging impossible with so-called conventional setups. Acquisition performance benefitted from only having 6 km streamer lengths, with less infill and risk of tangles compared to continuous 12 km streamers. Indeed, a 3D streamer spread with continuous 12 km streamers has never been attempted. Processing treated the near and far offset ranges independently, without any compromise to, or revision of the processing flow applied to single vessel operations. Wavefield separation of the dual-sensor data removed the receiver-side ghost, and provides a platform for better multiple attenuation, velocity model building and reservoir characterization. SLO delivers less risk and greater efficiency in operations, whilst simultaneously improving target illumination and imaging in salt provinces.

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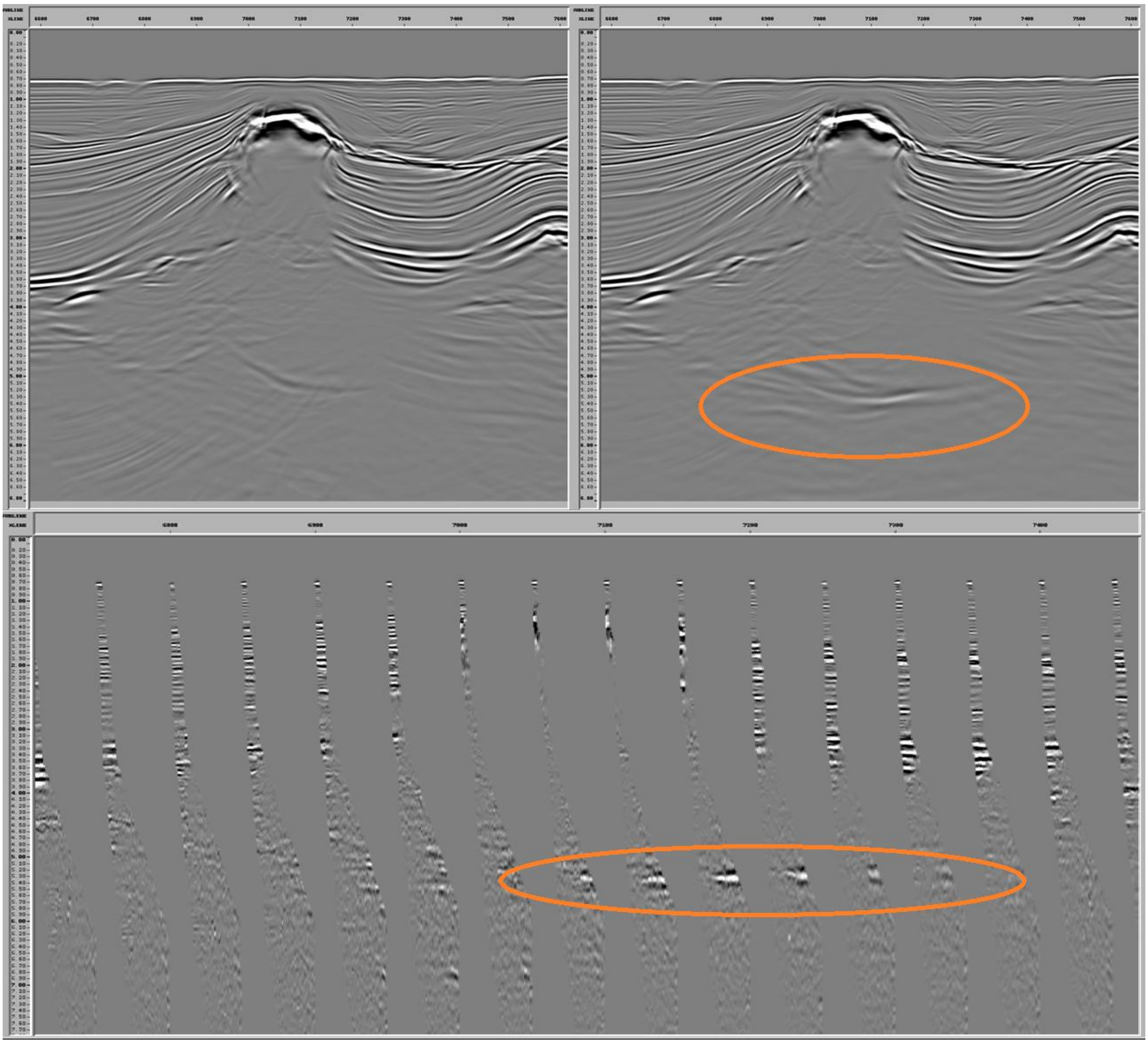

Figure 5. (Upper left) PGS beam PSDM result for 0.3 – 6.0 km offset, (upper right) PGS beam PSDM result for 0.3 – 11.9 km offset, (lower) Beam PSDM 0.3 – 11.9 km image gathers after NMO correction and 15-45º angle mute applied. Note the spatially-variable contribution of very long offset reflection events to both image gathers and stacks.