Seismic efficiency on a vast scale – a case study from offshore Gabon

Luke Twigger[1*], Rob Schouten[1], Guy James[1] and Jo Firth[1] demonstrate how they unlocked the potential of one of the last underexplored regions of the South Atlantic margin through smart seismic acquisition, processing technology and close collaboration.

Seismic surveys come in all shapes and sizes, depending on factors such as objectives, geographical area, geological environment, local licence requirements, and budget.

Small surveys over a focused area can make sense individually, though there may be inefficiencies, such as many vessel turns when recording short lines. When several such surveys are located near by there can be both gaps in coverage and redundancy of the aperture needed to ensure that areas of interest are fully imaged. Moreover, velocity models may seem fine-tuned for each individual survey but frequently do not connect together smoothly when examined on a regional scale. At some point, it makes more sense to acquire and process one large survey rather than several smaller pieces.

Multi-client surveys provide a cost-effective route to large, high-quality datasets. Costs are shared, so larger surveys can be acquired, for a better overall view of the prospectivity than is generally the case with smaller, proprietary surveys. Access to large surveys, in both mature and frontier areas, allows companies to reduce their exploration risk. It can also help to cut the time between the award of a licence and the drilling of the first well.

Such an example of a large, multi-client survey is a project carried out recently by CGG offshore Gabon. This was designed to cover all five licence blocks in the 11th Licensing Round with one vast 3D survey, providing a contiguous broadband seismic dataset over the whole area. This turned out to be some 25,000 km² in extent. To put

***Figure 1** It is hard to appreciate the scale of a 25,000 km² area of the Atlantic Ocean, but it is significantly greater than the ~20,000 km² occupied by the whole of Wales.*

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this into context: 250 km² might cover a typical North Sea field development survey; 2500 km² could be an exploration survey in a deepwater area offshore Brazil or cover more than 1000 OCS blocks in the Gulf of Mexico; 25,000 km² is a whole order of magnitude larger still.

The goal was to unlock the potential of this prospective area, one of the last underexplored regions of the South Atlantic margin. Only through efficient use of smart seismic acquisition, processing technology and close collaboration between all involved parties could high-quality results be delivered in a timely fashion for the licensing round.

Underexplored frontier

The survey location is shown in Figure 1. To demonstrate the scale of this project to those unfamiliar with the geography of Gabon, the inset image compares the survey outline to a map of the UK. A total of 11 licence blocks were covered offshore Gabon in a wide span of water depths ranging from 90 to 3600 m.

The geology of this salt-dominated area is highly complex, (Duval and Firth, 2015). Exploration targets show great variety from deep, subsalt sandstones, through suprasalt carbonate 'turtlebacks' which can provide good reservoirs locally, to turbidite sands that constitute well-known objectives farther south in the waters of Angola and Congo. Pre-salt traps comprise tilted fault blocks and transpressive structures sealed by shales or salt. Post-salt traps comprise drapes over salt domes sealed by shales or combination structural/ stratigraphic traps of sand-rich channels within turbidite systems. Figure 2 expresses the current geological understanding in schematic form.

Thus far, there is little known about the distribution of source rocks and reservoirs in this underexplored region. Early interpretation indicates the presence of thick syn-rift and sag sequences below the salt, which are key intervals of the pre-salt petroleum system. This survey and related work will no doubt contribute hugely to the understanding of this deep offshore area.

Simultaneous acquisition

The first challenge is to acquire a survey of such a size in as an efficient and timely manner as practicable. One obvious way to speed up acquisition is to deploy multiple vessels. Two fully-equipped seismic vessels gather data twice as quickly as one and hence halve the survey time. In practice, it's not quite that simple, due to the issue of seismic interference, whereby one vessel's receivers pick up signals generated by the other vessel's sources. The nature of this interference varies with the proximity and relative direction of the two vessels and their streamer arrays.

The vast size of the survey area was beneficial in this regard as the vessels could often be well separated, thus reducing the amplitude of any interference. The nature of the deepwater environment offshore Gabon means seismic interference has less impact when compared to shallower areas such as the North Sea. However, to avoid any compromise in data quality, the survey also employed a proprietary system known as SynAcq, used previously in the North Sea. This allowed both vessels to work semi-independently, making use of advanced navigation tools that allowed the planning and management of seismic interference, so as to avoid any noise that could not be readily attenuated in processing. Onboard processing tests ensured that any contamination that did occur would not compromise the primary data (Elboth and Haouam, 2015) and a seismic interference attenuation processing flow was applied, delivering clean seismic data from both vessels.

The seismic survey was acquired in just nine months by two vessels operating simultaneously. Each vessel towed a spread of 10 x 10 km streamers, at 120 m separation.

The survey was acquired and imaged using a variable-depth streamer tow for broad-bandwidth data (Soubaras and Dowle, 2010). The streamer shape enables the majority of the streamer to be towed deep, down to 50 m. This deep tow enables the recording of the ultra-low frequencies required for pre-salt imaging; it also avoids much of the sea-state noise, thereby extending the weather window for greater operational efficiency and contributing to faster turnaround times.

Cascaded processing

A survey of this size pushes current seismic processing technology to the limit. Simply adding more computer power is insufficient; sophisticated methodologies and optimised algorithms are also required in order to overcome existing production bottlenecks.

A common way to reduce overall turnaround for datasets is to begin processing the seismic data onboard the vessel while acquisition is ongoing. Seamless integration of software tools, workflows and processing expertise between offshore and onshore teams allows work in the processing centre to continue right from the point at which the offshore geophysicists hand it over.

On this project, cascaded processing flows were purpose-designed to meet different objectives: pre-stack time migration (PSTM) gave an early look at image quality; fast-track pre-stack depth migration (PSDM) provided a start on the structural interpretation; meanwhile, the main high-resolution PSDM flow benefited from lessons learnt on the two fast-track products.

An advanced onboard processing system on one of the acquisition vessels enabled a fast-track PSTM dataset for the 12,000 km² acquired by this vessel (half of the total survey area) to be delivered just three weeks after the last shot. Time tomography (Lambaré et al., 2009) was used to quickly derive an accurate migration velocity to use for the fast-track PSTM. This not only updated velocity but also

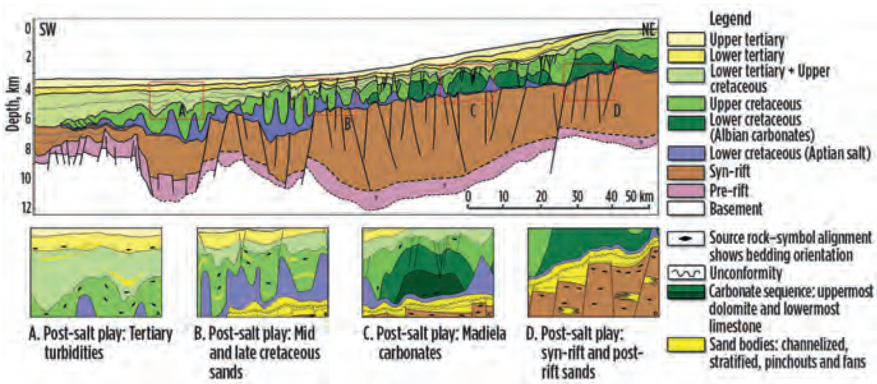

***Figure 2** A schematic showing the geology of the Gabon South basin cross-section, with illustrations of some of the potential play concepts, from Duval and Firth (2015).*

the anisotropy parameters. Work then continued onshore, following on from the pre-processing performed offshore on both vessels, so that the fast-track PSTM for the full survey was completed within three months after the end of acquisition. Figure 3 shows an example from this, illustrating the data quality of the broadband acquisition.

As can be seen in Figure 3, the complex geology of this area presents severe challenges for time migration. Hence PSTM was only used for the first fast-track product. Thereafter, all work was carried out in depth migration flows, rather than expending further effort trying to improve time migration products. A sample area of fast-track PSDM was delivered four months after acquisition, to demonstrate the full potential of the data. This is illustrated in Figure 4, which compares PSTM and PSDM for the same crossline.

Vital collaboration

Any project relies on good collaboration to progress in a timely manner. This was especially true on this large, important survey with many stakeholders, including the Gabonese government Direction Générale des Hydrocarbures (DGH) and international oil companies. Each contributed different resources and expertise, for example, the Gabonese government provided valuable data from wells in the area while oil company interpreters helped to decipher the complex stack of salt and carbonate bodies.

Modern communications technology played a crucial role in bringing together representatives on different continents and in different time zones, allowing them to work together productively. This project made use of a technology solution to enable secure remote access, SAFRA (Secure Access For Remote Applications), to provide a step-change in high-performance remote working. Stakeholders were given independent and continuous access to seismic databases and proprietary software packages to perform tasks, such as QC and interpretation of seismic volumes and PSDM velocity model updates. This allowed the various stakeholders to contribute their expertise and critical geological knowledge to the interpretation and velocity model design for this frontier area.

This project is about much more than just the seismic data. A wide range of geoscience data is being brought together to provide a better understanding of the region's prospectivity. Gravity measurements were acquired onboard the seismic survey vessels and were used to constrain the interpretation and velocity modelling. A comprehensive geologic review is underway to investigate source and reservoir presence and maturity as well as the timing of pre-salt trap formation and its impact on the generation, migration and entrapment of hydrocarbons.

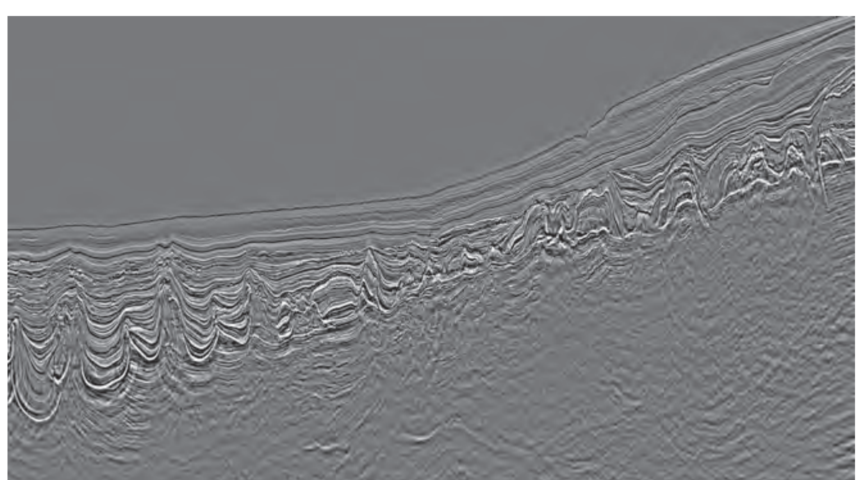

***Figure 3** The shallow section of this fast-track PSTM inline showcases the high resolution that broadband seismic brings, while demonstrating the challenges of imaging the deep data, which need PSDM to be fully resolved.*

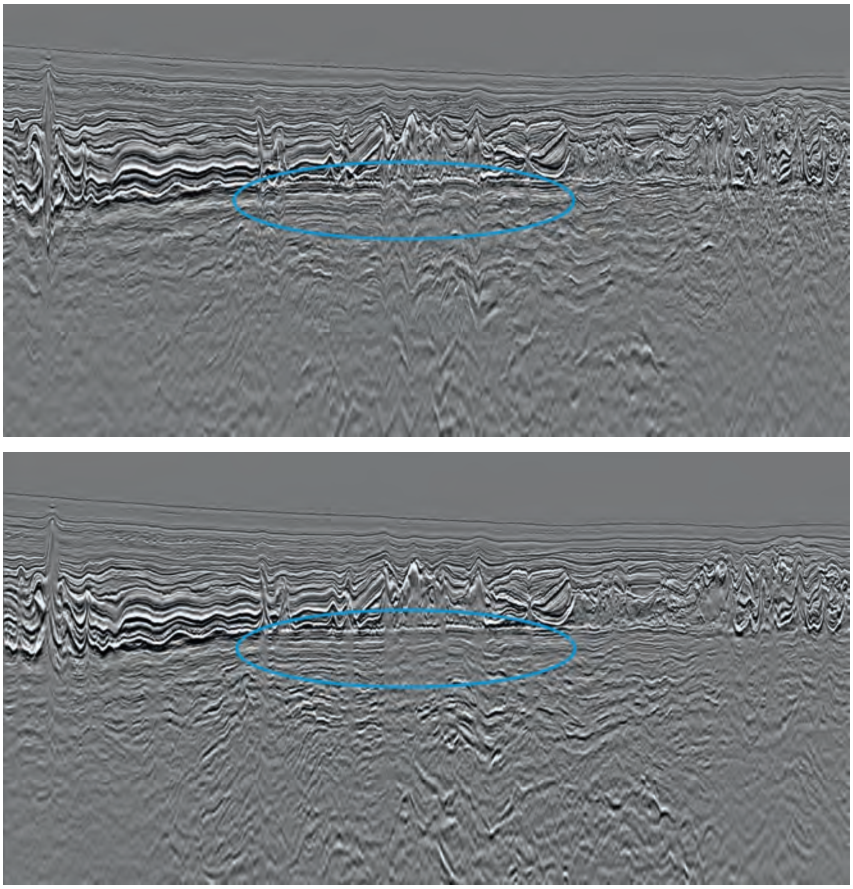

Figure 4 *a) This crossline taken from the fast-track PSTM dataset (displayed in depth) demonstrates issues caused by the highly challenging shallow structure on the deeper data – notably the push-down effects annotated in blue.*
b) The same fast-track crossline taken from an anisotropic PSDM output during the iterative multi-layer tomography demonstrates the uplift provided by the depth migration flow. The push-down effects have been resolved and the deeper pre-salt structure can now begin to be appreciated.

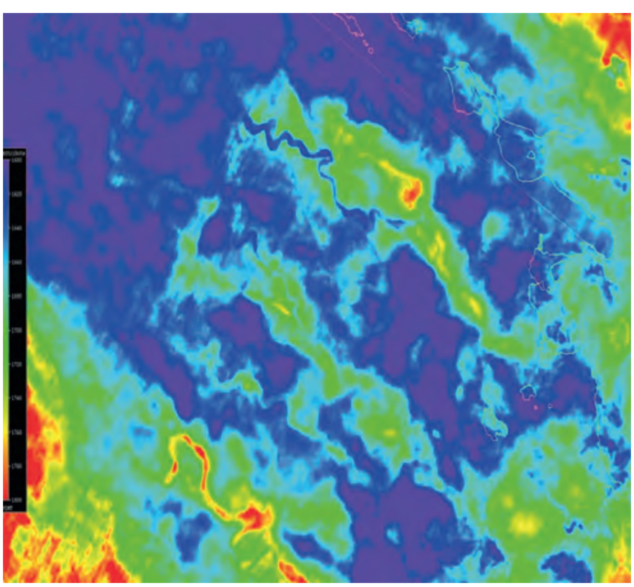

Figure 5 *Slice at 3500 m depth through a ~2500-km² portion of the FWI velocity model, demonstrating the level of detail picked out by the method such as meandering channel features.*

It will also look at the regional geological context from a plate tectonic timing perspective and provide regional palaeogeographic maps for key periods addressing the play elements. This geological review also benefits from satellite Synthetic Aperture Radar (SAR) mapping of offshore hydrocarbon seeps, indicating active petroleum systems in the region.

Broadband deghosting

This project benefited from some of the latest broadband seismic processing techniques, carefully designed and optimised to work consistently across this vast survey, even with a large variation in water depth.

To facilitate accurate source deghosting, near-field hydrophone responses were measured for every shot in the survey. These were used to estimate individual shot-by-shot far field signatures, which deliver a better estimate of the bubble and the low-frequency signal compared to conventional pressure field modelling (Ziolkowski, 1982; Poole, 2013; Ni, 2014). This enabled accurate designature throughout the bandwidth, encompassing de-bubbling and zero-phasing in one step, to remove the imprint of the marine source system from the images and attributes of the subsurface.

The accurate source designature and deghosting was complemented by pre-stack 3D receiver deghosting (Wu et al., 2014), which used a progressive sparse Tau-Px-Py inversion, ensuring the receiver ghosts were correctly handled in this area of complex geology. This combination of full 3D

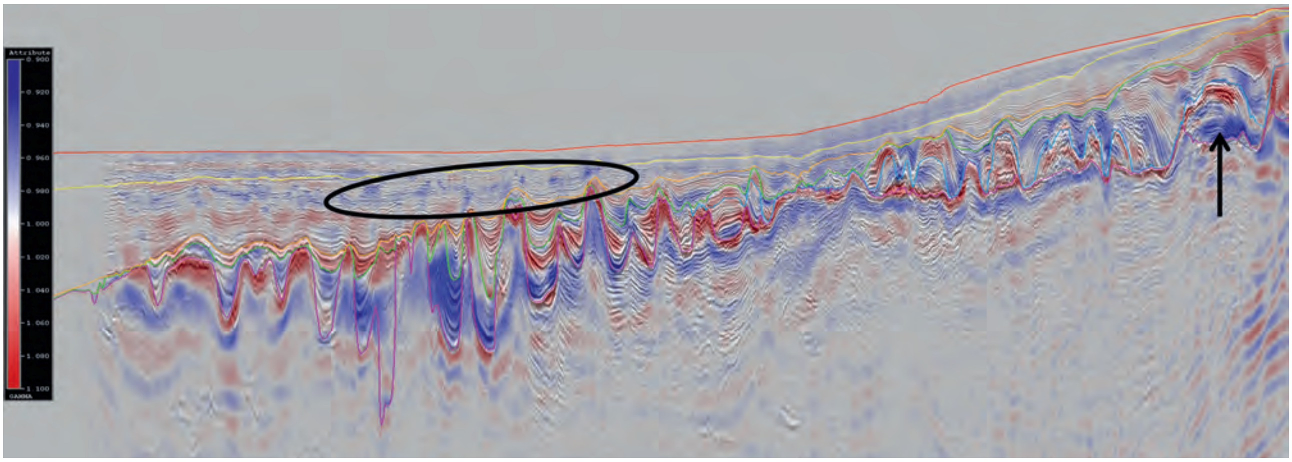

Figure 6 *The colour overlay on this 120-km-long inline section depicts velocity perturbation derived by the FWI. Shallow gas pocket anomalies are evident, indicated within the black oval. A 'turtleback' structure is marked with the black arrow. The pink horizon indicates the top salt interpretation.*

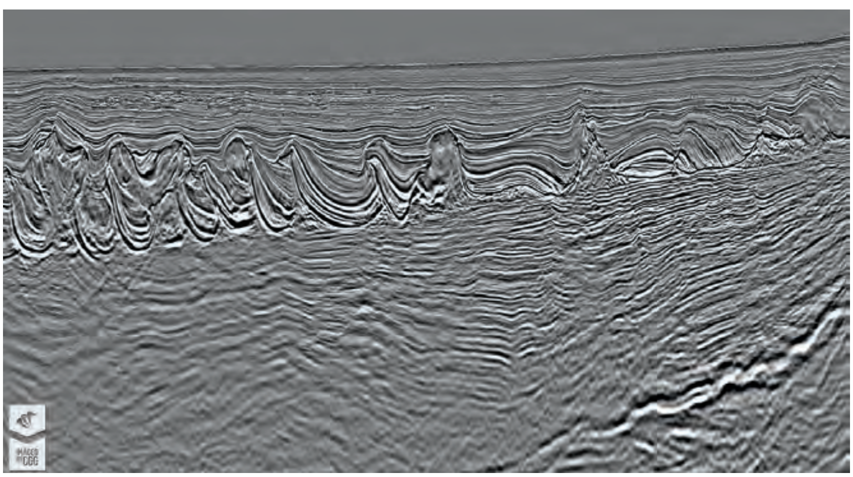

Figure 7 *This fast-track RTM section demonstrates the uplift delivered in the deeper section. Heavily faulted syn-rift structures are revealed below the salt with a pre-rift section in the bottom right corner.*

source and receiver deghosting delivered the sharpest possible broadband wavelets with stable and accurate low frequencies.

Velocity model building

The PSTM velocity model was used as the starting point for multi-layer non-linear slope tomography (Guillaume et al., 2012) to update the velocities for the PSDM flows. The tomography was constrained by an initial seismic interpretation and a depth-to-basement map derived from gravity data acquired simultaneously with the seismic data. Here we drew on prior experience from a 35,000 km^2 project in the North Sea (Hollingworth et al., 2015). Multi-layer tomography provides geologically-consistent regional trends while retaining the fine details normally associated with smaller, reservoir-focused PSDM projects.

Two model building unit updates were applied down to the top of the salt, including geomechanical modelling to resolve near-surface anomalies such as deep canyons. This was followed by interpretation of the top salt boundary and testing of salt velocities to construct a salt model and then a full-area reverse time migration (RTM) for base salt interpretation. After salt body insertion, the pre-salt was updated tomographically before a final phase of RTM imaging, interpretation, salt body modelling and pre-salt velocity analysis. Collaborative efforts between interpreters from different companies was key to achieving the best possible interpretation of the salt and carbonate bodies, a critical stage of the velocity model building. In fact, the interpreters produced what is believed to be the largest salt model interpretation ever performed on a single survey.

The final model derived from the multi-layer tomography was then input to full waveform inversion (FWI) to further refine the detail of the shallow velocity structure. Just a couple of years ago the prospect of applying FWI to such a large dataset would have been incomprehensible. Recent advances in both algorithms and compute power have made FWI much more accessible for large-scale production processing. FWI was applied over the entire 25,000 km^2 area down to the maximum depth reached by diving wave penetration, which, for this dataset acquired with 10 km-long streamers, effectively coincides with the top salt boundary. The high-quality, low-frequency data acquired using the variable-depth streamer profile with full 3D source and receiver deghosting is particularly beneficial for FWI as the enhanced low frequencies help to prevent cycle-skipping. Figure 5 demonstrates some of the details captured in the FWI velocity model.

The FWI has provided evidence of low-velocity gas pockets, usually located directly above the salt diapirs. Incorporating these anomalies into a detailed velocity model mitigates the push-down effects that these usually cause on seismic images and thus improves the image in both shallow and deep sections. It also yields additional useful information about the near-surface and possible geohazards. Figure 6 shows a regional cross section through the heart of the survey, with FWI velocity perturbation QC overlain in colour to indicate where FWI has modified and added detail to the input tomographic velocity model.

RTM was used for the main PSDM flow. This took full advantage of the strong low-frequency energy inherent to the broadband seismic. It was able to fully honour the fine detail in the velocity model delivered by the multi-layer tomography and FWI workflow. Figure 7 shows an example of a fast-track section, where deep structures beneath the salt can now be seen and interpreted.

Conclusion

This project demonstrates the scale of what can be achieved through a combination of technology, project management, expertise and collaboration. The time frame for the delivery of this vast 25,000 km^2 dataset would not be considered unreasonable for a project one tenth of its size. This has been accomplished while applying a premium processing sequence utilizing the latest techniques most appropriate for this complex area.

The final combined geoscience package will provide new insights into the prospectivity of deepwater offshore Gabon and benefits from a wide breadth of expertise spanning geology, geophysics, integrated interpretation and reservoir characterization, brought together in a unique collaborative environment.

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