Acquisition of long-offset data offshore Gabon shows how synchronized source technology adds flexibility to tailored acquisition solutions

Thomas Mensch[1], Krzysztof Cichy[1], Risto Siliqi[1], Jo Firth[1*] and Benoit Jupinet[1] show how advances in equipment, technology and de-blending and cross-talk attenuation algorithms in processing have enabled blended acquisition offshore to become a realistic option.

The current climate in the oil exploration industry has engendered a strong push towards efficiency in acquisition. One technique that offers this is synchronized sources, or SyncSource, where sources are activated before the recording of data from the previous shot has been completed. As this may result in significant overlap of seismic data between successive shot records, it means that the data must be de-blended to recover the individual contribution from each source. However, this makes it possible to acquire data with higher trace density, smaller bins or longer records than can be achieved using conventional acquisition techniques. The simultaneous shooting technique has been commonly used in land acquisition for some years and its potential for ocean bottom and towed-streamer acquisition has been well documented (e.g. Moore et al., 2012; Davies et al., 2013; Poole et al., 2014).

As long as the de-blending can be performed successfully, without compromising the data quality, there are many advantages to synchronized source acquisition in terms of quality and efficiency, based on the fact that the sources can be activated more frequently. This offers options for new acquisition geometries that had previously been either impossible or prohibitively expensive. It becomes possible to maximize efficiency either by increasing vessel speed without increasing shotpoint interval or reducing record length, or by reducing crossline bin spacing by adding a source rather than by reducing cable separation. Superior resolution can be achieved with a finer shot grid and a higher trace density to deliver higher-fold images with better signal-to-noise ratio and smaller bin size. Better illumination at depth can be achieved by increasing the recording time with the optimal source-receiver offset and

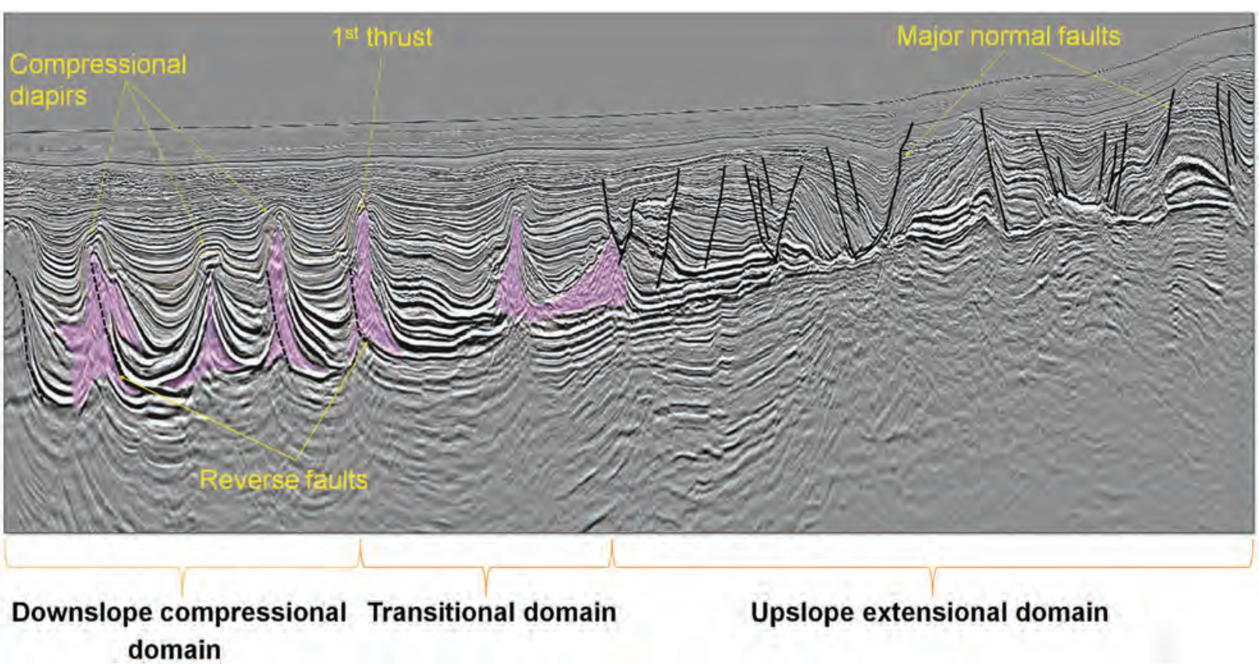

Figure 1 *Interpreted fast-track data showing the regional geology of Gabon's South Basin (image courtesy of CGG Multi-Client & New Ventures).*

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azimuth, through the deployment of additional source vessels, without compromising the shot density or acquisition time.

Recent advances in acquisition equipment and technology have combined with advances in de-blending and cross-talk attenuation algorithms in processing to allow blended acquisition offshore to become a realistic option. We have successfully conducted a full-scale commercial survey of 2500 km^2 using this technology in order to acquire ultra-long offset data offshore Gabon.

In Gabon's South Basin, the geology is very complex with both pre- and post-salt plays, while compressional zones and salt basins cause challenges for illumination and imaging. This area is in a continental passive margin and exhibits the classic characteristics of a gravity-driven collapse system (Figure 1). Upslope, there is a broad region of extension, with normal faulting, rollover anticlines, thin salt with pillows and carbonate rafts. Downslope, there is a compressional domain with thrust faulting, folds, tilted diapirs and complex extruded salt structures. In between there is a transitional zone of upright diapirs and local welds (Xiao et al., 2016).

Modelling

Wave equation modelling was performed in the more complex downslope compressional area to examine the effect of longer offsets on illumination using a number of techniques. Specular rays, illuminating the pre-salt reflectors and emerging to the surface with a fan of offsets (Figure 2), showed that to acquire incidence angles beyond 20 degrees from the pre-salt, an acquisition with offsets longer than 10 km is required. Moreover, diving ray analysis using the most accurate model of the subsurface to date, derived from tomography on new broadband seismic acquisition, suggested that diving rays acquired with a 14-km offset are able to provide some pre-salt velocity information when a 10-km offset could not (Figure 3). On the other hand, the large number of ray paths emerging beyond the 10-km offset could substantially improve Full-Waveform Inversion (FWI) results. Since modelling showed that longer offsets and additional azimuths should improve the imaging of the pre-salt targets, it was decided to supplement the existing broadband seismic data, acquired using offsets of up to 10 km, with an additional acquisition of orthogonal azimuths, including extra-long offset data to 14 km, over an area of about 2500 km^2 in the south of the Gabon South Basin.

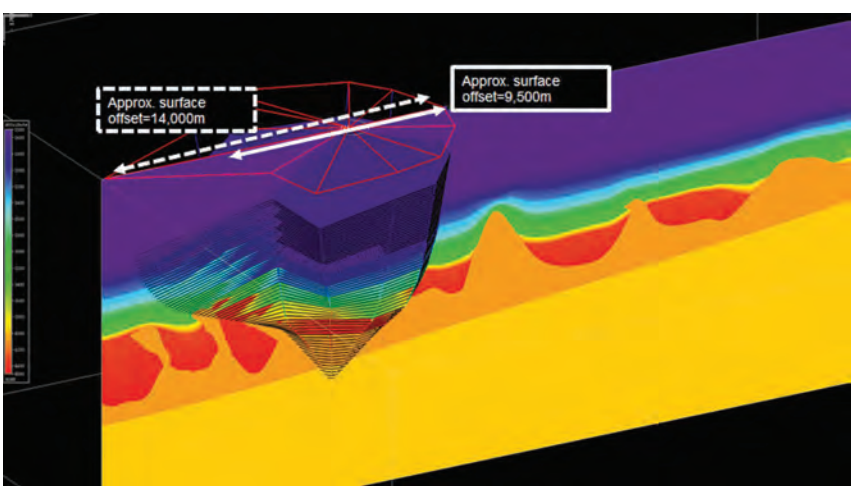

***Figure 2** Velocity model and specular ray from pre-salt reflector.*

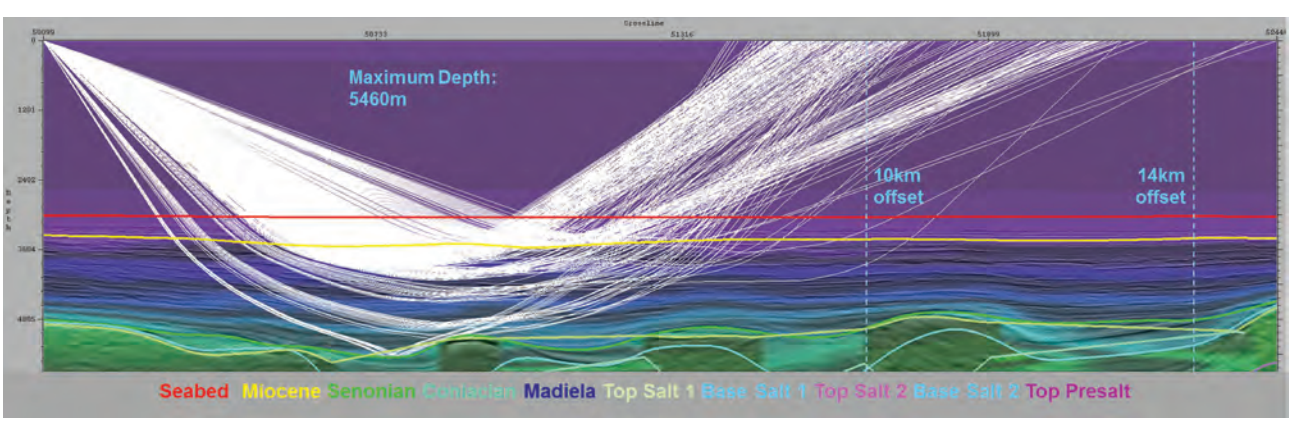

***Figure 3** Diving ray analysis incorporating 15-km maximum offset and 15-second maximum recording time.*

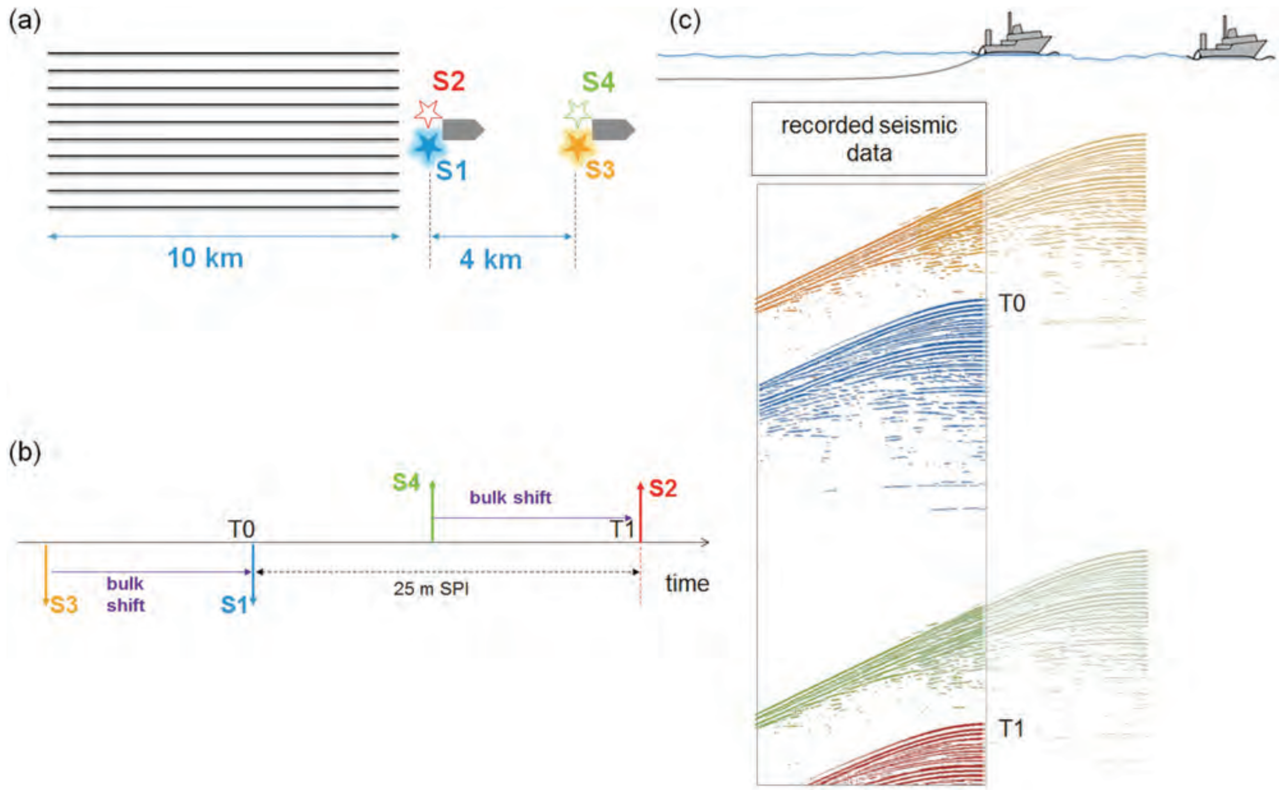

Figure 4 *Dual-vessel geometry for long-offset acquisition. (a) An additional source vessel is deployed 4 km in front of the streamer vessel with both vessels towing two seismic sources. (b) A dedicated shooting sequence is applied for acquiring blended seismic data with activation of the sources being synchronized by pair. A constant bulk shift between synchronized sources controls the energy overlap between short- and long-offset data. (c) Example of recorded blended data.*

Acquisition

An efficient way to acquire seismic data with 14-km offsets is the extension of the acquisition system to use an additional source vessel. By deploying an extra source vessel 4 km in front of the streamer vessel (Figure 4), it is possible to extend the offset range to 14 km while using the same 10 x 10 km streamer configuration as used for the previous broadband survey, but in this case acquired with a perpendicular azimuth. This design preserves the continuity of the receiver depths as a function of offset. The seismic data with offsets below 10 km are acquired by the full streamer length after activation of the sources towed by the streamer vessel, while the longer offsets from 10 km to 14 km are acquired by the deep flat part of the receiver spread (from 6 to 10 km) after activation of the sources towed by the source vessel. The most efficient way to maintain the shot density and fold without slowing down the speed of the vessels is to overlap the extra-long offset wavefield with the conventional 10-km offset data.

To record seismic data at such long offsets with a dual-vessel configuration has a significant impact on both the shooting strategy and the acquisition system. In order to maintain the 25-m shotpoint spacing, the seismic sources have to be activated twice as often as for conventional single-vessel acquisition. This preserves the seismic fold for all offset classes, as well as the efficiency of the acquisition by maintaining the same vessel speed. However, it results in blended data acquisition with significant energy overlap in the seismic records, which has to be properly separated and removed at the processing stage.

In order to optimize the separation process (de-blending), a specific shooting strategy has to be carefully configured (Figure 4b). An example of blended data acquisition is illustrated in Figure 4c. The distribution of the energy in the seismic data is controlled by the time delay between the activation of synchronized sources, necessary to control the energy overlap between the short-offset and long-offset data, and additional calculated delays for facilitating the de-blending process.

Such an acquisition strategy requires an up-to-date acquisition system. It strongly relies on continuous recording technology which allows proper handling of the overlapping seismic records and guarantees the integrity of the seismic data. In addition, the SeaProNav system, which directs the marine acquisition, was upgraded by Sercel in order to implement the complex shooting sequence accurately.

The selection of the right de-blending algorithm and the deployment of individually designed source activation

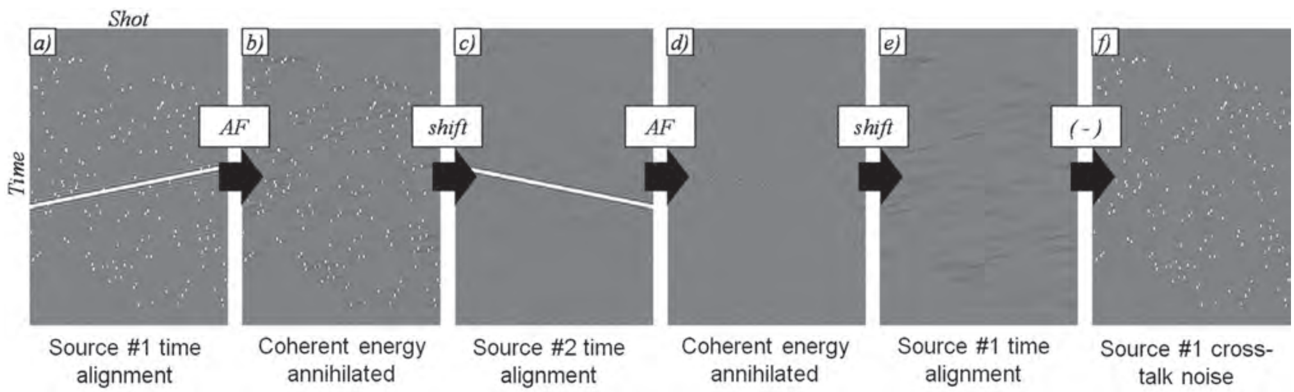

Figure 5 *Common-channel schematic showing one iteration of the de-blending workflow for one source. (a) blended data aligned for source #1, (b) result of first annihilation filter, (c) data aligned for source #2, (d) result of second annihilation filter, (e) after reversing the time shifts, and (f) result of subtracting (e) from (b) (from Rohnke and Poole, 2016).*

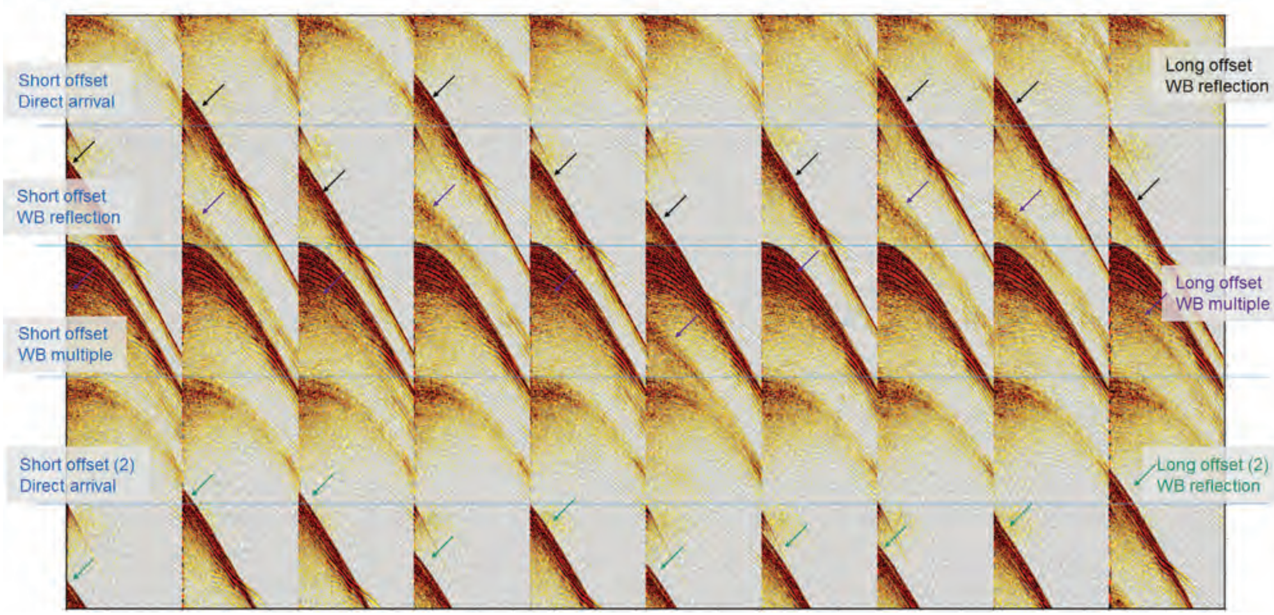

Figure 6 *Shots input to de-blending. The lines indicate short offset aligned around the direct arrival and arrows indicate reflections scattered from shot to shot relating to energy from other sources.*

sequences, adapted to the geological context, are vital to deliver well-separated shot records.

De-blending

Once blended data have been acquired the shots have to be separated. In order to facilitate this process, calculated asynchronicity is introduced into the source activation times from shot to shot, to ensure that energy from the second source appears as random and impulsive cross-talk noise, when sorted out of shot order. Conversely, realigning the data to the second source time results in randomization of the first source. Cross-talk noise for each source alignment can then be attenuated using impulsive denoising techniques (Stefani et al., 2007).

Several methods of de-blending are available; our preferred technique is the use of iterative annihilation filters (Rohnke et al., 2016). In this proprietary method, annihilation filtering is used to build a cross-talk model that can be realigned according to the known timing delays to represent the unblended data. Annihilation filters are defined as filters which attenuate coherent energy, such as prediction-error filters. These remove the predictable part of the data, effectively leaving the unpredictable part intact. We use a high-resolution sparse tau-p transform (Trad et al., 2003) which has been modified to calculate the residuals in the time domain (i.e. the cross-talk noise) directly.

An annihilation filter is applied to the data where the first source is coherent (Figure 5a) and significantly attenuates the energy for this source. However, although the cross-talk noise is left largely intact, it is smeared by the effect of the filter (Figure 5b). To mitigate this effect the data are shifted by the known time delays so that now the energy from the second source is coherent and the attenuated energy from the first source becomes the incoherent noise (Figure 5c). To attenuate the coherent energy from the second source a second annihilation filter is then applied, leaving the remaining cross-talk noise from the first source largely intact (Figure 5d). When the time shifts are reversed again (Figure 5e) and the result is subtracted from the output of the first annihilation filter, the attenuation of energy from the first source is improved while the effect on the cross-talk noise is minimized (see Figure 5f).

The same flow is repeated, starting with the second source being coherent, and the results for both sources are subtracted from the input data, to leave the residual as the input for the next iteration. The process is iterated, summing the results from each step until the residual is sufficiently small. The residual energy can be added to both de-blended results after the last iteration, which ensures that all energy has been preserved.

Results

Some real blended shot records from the Gabon survey, without the correct time origin, are shown in Figure 6. Nevertheless, for the short-offset data the direct arrivals are aligned, as well as the water bottom reflector and water bottom multiple, as the sea floor here is relatively flat. Due to the asynchronization timing shifts, the long-offset data are not aligned across all the seismic traces, so these water bottom reflectors and multiples arrive at different times on each record. Figure 7 shows duplicated shot gathers before and after de-blending into independent short-offset and long-offset records (still without the correct time origin). The de-blending process successfully separates the two sets

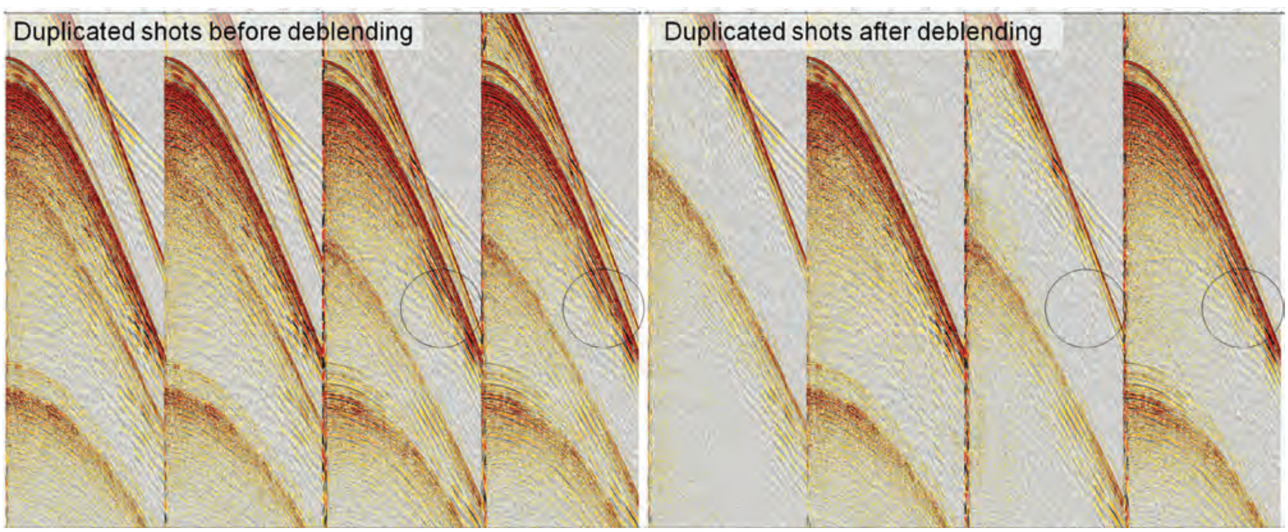

Figure 7 *Duplicated shots before and after de-blending. The de-blending process successfully separates the two sets of data, even where the short-offset and long-offset water bottom reflectors arrive at approximately the same time (indicated by the circle).*

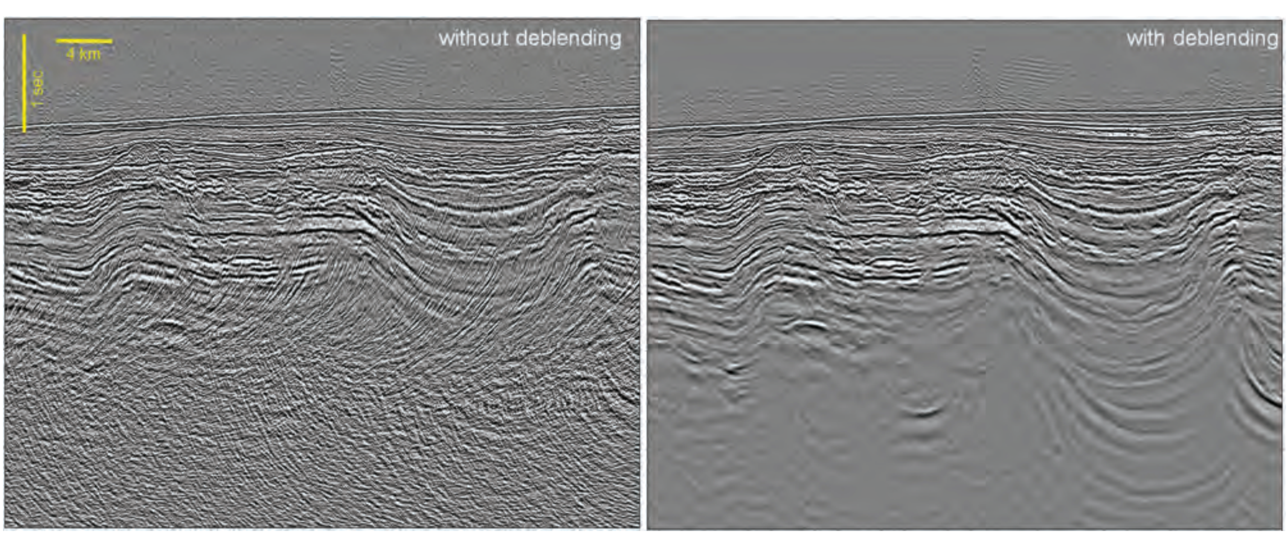

Figure 8 *Comparison of PSTM stacks for the long-offset data with and without de-blending.*

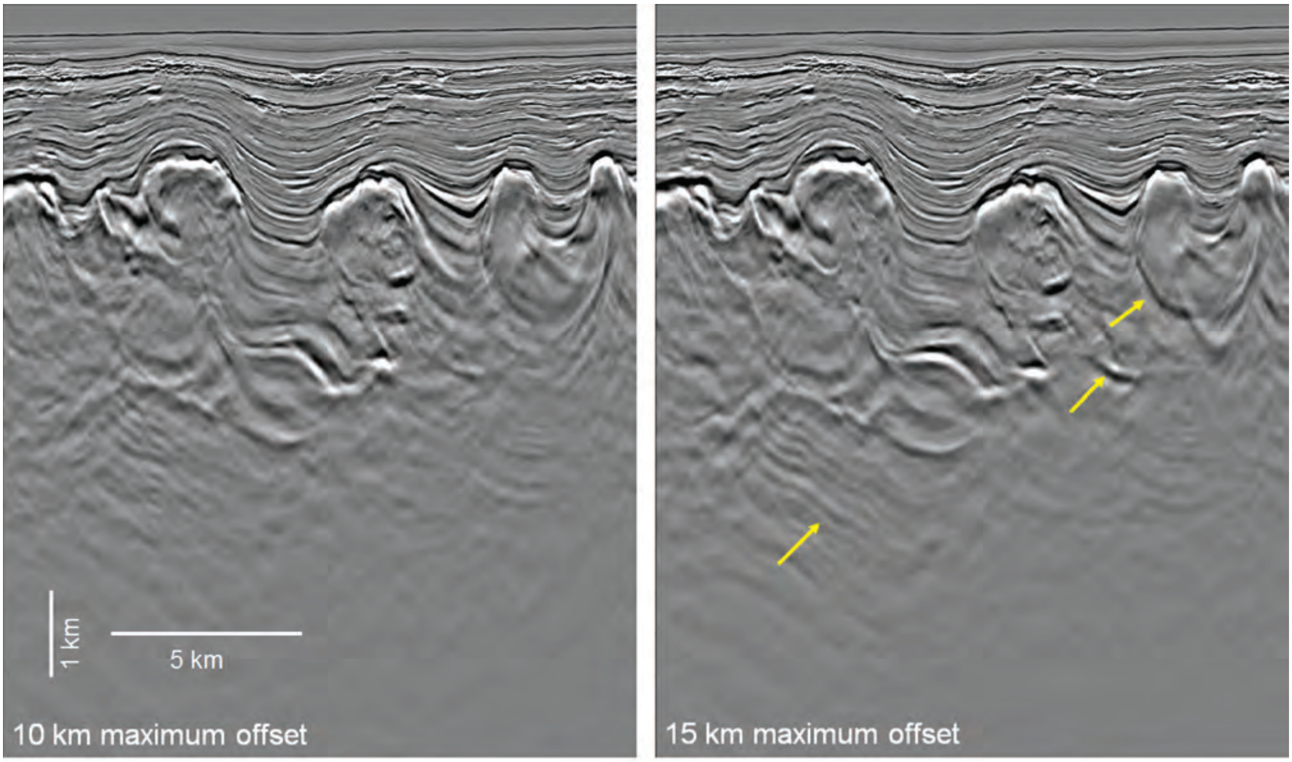

***Figure 9** Comparison PSDM stacks, from a nearby area. Imaging using seismic data with up to 15 km offset showed improvement in the pre-salt over imaging using a maximum offset of 10 km.*

of data, even in the challenging situation where the short-offset and long-offset water bottom reflections are superimposed (indicated by the circle), with very little leakage of signal and low levels of residual cross-talk noise.

Among the many quality control procedures performed during the de-blending process, a time migration is performed to check residual noise levels. As the amplitude of long-offset reflections is weak compared to short-offset seismic events, and owing to the strong degree of randomization of the cross-talk noise, there is little difference between the near-offset image stacks of blended and de-blended data. However, because of this dominance of the short-offset energy, there is a significant difference between the blended and de-blended data on the far-offset image stacks (Figure 8). The de-blending process can be seen to have successfully separated the data from different sources. Systematic testing of the iterative annihilation filtering approach (Rohnke and Poole, 2016) demonstrated that the amplitude error induced by de-blending is about 30 dB lower than the level of the signal.

The motive for acquiring up to 14-km offset data using blended acquisition technology was to capture additional energy around highly complex salt formations to add additional resolution to our velocity model and, if possible, supplement the illumination of the pre-salt in a data set already demonstrating excellent imaging results. In addition, these data are being acquired orthogonally to the previous survey which will deliver a dual-azimuth data set with added benefits for pre-salt illumination. The imaging of this data set is still in progress and although no comparisons are yet available, early tests show promising results. However, additional long-offset data acquired near by have shown improvement for deeper pre-salt reflections as a result of the extra 5 km of offset. The tomography of pre-salt velocity has been substantially improved thanks to the unique long-offset RMO (residual moveout) information. This has resulted in better stack imaging of pre-salt structures (Figure 9), where the additional longer offsets also helped to improve the signal-to-noise ratio. In this case, there was no second azimuth acquired so all the benefit was purely owing to the longer offsets.

Conclusion

The ultra-long offset Gabon survey represents just one of the varieties of acquisition geometry that become available when energy from different sources is allowed to overlap in the seismic record. Freeing the geometry from the necessity of activating sources sequentially, after recording the full record length, enables a considerable increase in source density and consequent flexibility in acquisition design. This applies even to acquisition using only one vessel, but is increased substantially if more than one vessel is deployed, as the relative positions of the sources and streamers can be manipulated to deliver a variety of offsets and azimuths, without the need to increase individual shotpoint intervals. The deployment of SyncSource in single-vessel acquisition allows the safe use of triple sources to enable wider streamer separation, without modifying inline shot density and fold. As a result of de-blending capabilities, vessel speeds can be increased without reducing record length or increasing shotpoint interval. Synchronizing the sources of an additional source vessel enables the achievement of an ultra-wide spread for greater efficiency and extra offsets and/or azimuths for better illumination. Continual advances in subsurface imaging technology mean that improvements in de-blending algorithms are constantly being developed. As sources can now be placed anywhere without the need to increase the individual shotpoint spacing, surveys can be designed to overcome all manner of challenges and can be individually designed for the optimum geometry for each specific target.

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