Benefits of integrated approaches for solving imaging challenges presented by complex geology: latest developments in marine wide- and full-azimuth surveys

Conrad Judd[1*], Risto Siliqi[1], Fabrice Mandroux[1], Jo Firth[1] and Chu-Ong Ting[1] present examples of wide-azimuth and full-azimuth acquisition technology in salt-dominated petroleum systems to ensure delivery of optimal data.

In salt-dominated provinces we are predominantly faced with complicated structures. In many instances, this can be characterized by irregular salt bodies with elaborate morphologies and interfaces manifesting high acoustic impedance contrasts with the surrounding substrate. Further complexity can be found in these surrounding layers, typically consisting of deformed anisotropic sediments. These challenging structures propagate heavily distorted wavefields, and as a result, seismic datasets have been frequently compromised by irregular and poor illumination, resulting in loss of definition and poor spatial positioning, especially at salt flanks, base salt and in the pre-salt strata.

Overcoming these challenges frames the setting for designing optimal survey parameters in the salt-dominated petroleum systems of the Gulf of Mexico, South American and West African continental margins, and the Red Sea. These challenges call for data with increased azimuth content, and the acquisition of such data in these regions suggests that the resulting benefits, such as improved signal-to-noise ratio, multiple suppression and anisotropy control, could be achieved in many other regions of the world where improvements over narrow-azimuth (NAZ) 3D data are required.

NAZ volumes result from the acquisition of data with a single vessel. By increasing options with the inclusion of additional vessels (recording and source vessels), we then create more opportunity to optimize an acquisition design that can provide a solution to the complex imaging challenges. Increasing azimuth content is not a simple panacea but with careful survey design, wide-azimuth (WAZ) acquisition technology and expertise, and the integration of these with the latest cutting-edge imaging solutions available, (such as Broadband, Full Wavefield Inversion (FWI), and improved velocity accuracy), we go a long way to ensure that delivery of optimal data is achieved.

WAZ acquisition history

The early stages of the switch to WAZ marine seismic occurred in the Gulf of Mexico in 2004, when CGG shot a WAZ survey for BP in order to improve illumination beneath tabular salt. At about the same time, multi-azimuth surveys were undertaken in both Egypt and the southern North Sea, in areas characterized with complex overburdens.

In addition to illumination improvements, one of the major findings of these early surveys was that multiple and noise suppression could be significantly improved by wide- and multi-azimuth shooting geometries. With this understanding, the benefits for other areas are being recognized as it becomes more widely realised that multi-vessel increased-azimuth recording can potentially provide a host of benefits in many different geological settings worldwide. These benefits include providing a clearer image of sub-basalt targets, reservoirs beneath rugose seabeds and deep targets with weak signal strength. Dense WAZ recording can also provide more reliable characterization of naturally fractured reservoirs.

Success requires the right design

Survey Evaluation and Design (SED), determining the principal ingredients of large-scale multi-vessel projects, such as azimuth, bandwidth, fold magnitude, fold distribution, offset and bin size, optimized within the available budget, is therefore key to their success. These studies develop WAZ acquisition designs that are tailored to the specific imaging challenges of the areas of interest. Designs are configured both to sample the wavefield optimally during acquisition and also with a view to the survey design being compatible with the specific requirements for effective seismic imaging during the data processing phase.

In addition, WAZ acquisition design has evolved in conjunction with other key improvements in seismic acquisition

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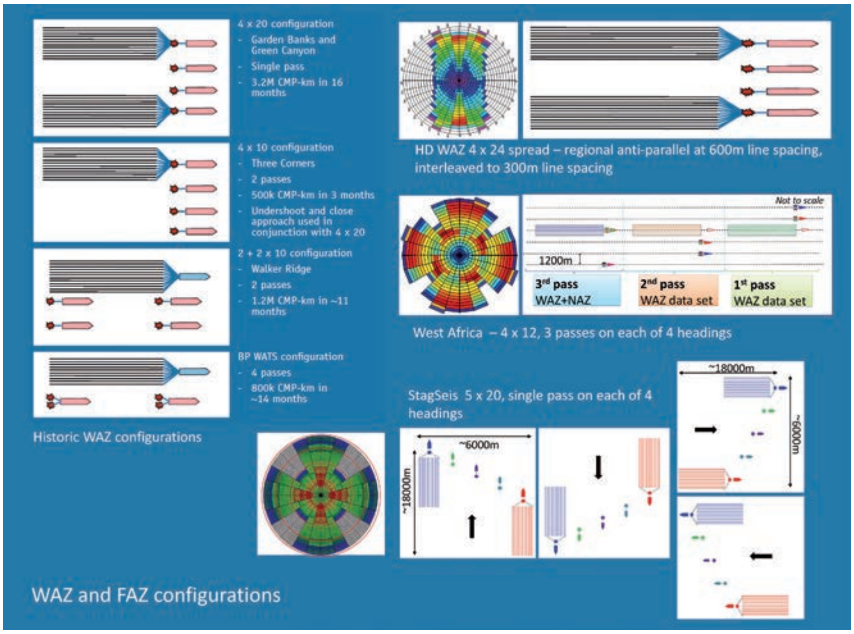

***Figure 1** WAZ and FAZ acquisition designs.*

and imaging technology to allow optimized configurations to be provided for specific imaging challenges.

Acquisition improvements

Among the many recent advances that have taken place in wavefield sampling and operational efficiency, the key improvements that have benefited WAZ acquisition are:

- Improved streamer technology, leading to improved low-frequency definition and better signal-to-noise ratio, as well as improvements in streamer handling, deployment/recovery efficiency and robustness.
- Raw data with broader bandwidth, achieved by addressing the issue at both the receiver and the source level. At the receiver end, various solutions exist to extend the bandwidth by addressing the receiver ghost. One solution achieves this by means of the deployment of a curved, variable-depth streamer, which exploits differences in receiver depths to produce receiver ghost notch diversity in the raw data, which then allows for effective deghosting of the data to broaden the bandwidth. Strong low-frequency raw data is obtained, without compromising the high frequencies. The technique capitalizes on the extremely good signal-to-noise characteristics and low-frequency response of solid streamers (Dowle, 2006). The ghost notch diversity is exploited by proprietary deghosting and imaging techniques (Soubaras, 2010; Wang, 2013), to produce a wavelet with both high signal-to-noise ratio and maximum bandwidth. Source solutions extend the frequency spectrum in the 100 Hz-200 Hz range, for example by means of a multi-level broadband source.
- Continuous recording: improvements in recording system technology allow the seismic record to be continually recorded throughout the seismic line, with shot records then reconstructed at a desired record length. In mid- and deepwater environments, this allows shot interval, record length and acquisition efficiency (vessel speed) to be optimized. The advantage of this method, in particular for WAZ acquisition where shot intervals tend to be larger than comparative narrow-acquisition geometries, is that a higher shot density (and therefore fold) can be maintained for a given record length and acquisition speed.
- Increased availability of large-capacity vessels, towing increased numbers of streamers of greater length.
- Streamer fanning: Significant reductions in infill are now routinely achieved on both wide-azimuth and conventional 3D acquisitions, by deploying streamers equipped with steerable devices in a fanned configuration.

Imaging improvements

The more extensive wavefield sampling provided by wide-azimuth acquisition delivers advantages and opportunities for imaging, such as improved noise and multiple suppression, improved illumination under tabular salt and more reliable anisotropy analyses. In order to reap maximum benefit from the azimuth sampling, techniques must be used that accommodate the true-3D nature of the wavefield; there are potential pitfalls in processing WAZ seismic data if such techniques are not employed.

True-3D algorithms have been designed to realize the full potential within WAZ data. By using all of the additional azimuthal information to deliver improved noise and multiple suppression from true-3D Tau-px-py and 3D high-resolution parabolic Radon transforms, accurate modelling and removal of multiples and coherent noise are ensured. The degree of improvement achieved in processes such as true-3D SRME, or de-multiple and de-noise using a 3D transform, depends on the data being well sampled. The data needs to be viewed and understood in terms of vector offset, not just in-line offset, and it is not only the maximum crossline offset but also the density of sampling of the vector offset that is important.

Well sampled, common vector offset cubes allow the preservation of azimuthal information throughout the imaging process, enabling more accurate estimation of azimuthal anisotropy. Efficient methods of azimuthal velocity analysis result in flatter gathers. 3D tomographic methods have been developed that incorporate the WAZ geometry when building an accurate depth model for migration. The additional azimuths provide improved illumination beneath complex overburdens and deliver superior images, especially pre-salt, using algorithms that take proper account of the anisotropy such as TTI (Tilted Transverse Isotropy) and Orthorhombic RTM.

High-resolution HD broadband wide-azimuth: Central America

Survey design

Legacy seismic datasets in the area of interest had limitations in terms of poor resolution due to limited bandwidth, missing fault plane definition due to poor velocity control and also suffered from low signal-to-noise ratio and multiple interference. High-density WAZ data were considered necessary to resolve critical imaging issues for existing prospects and allow optimal reservoir characterization to assist field development engineers.

This survey was designed for development of the extra-heavy oil fields in the region. State-of-the-art acquisition and recording were used to achieve high spatial resolution in both the inline and crossline directions, as well as high temporal resolution, with a variable-depth broadband streamer configuration providing ghost notch diversity and thus enabling a bandwidth from 2.5–150 Hz. An interleaved 4-source x 24-streamer configuration produced a final bin size of 12.5 x 25 m with a fold of 725. This was a dual-purpose development and exploration project, with about 70% of the acquisition covering development fields, and the remaining 30% allocated for exploration purposes.

Continuous recording led to the acquisition of a minimum useful record length of seven seconds, even in the deepwater areas. By using this technique, it was possible to overlap the shot records, so that deep data (beyond seven seconds) was recorded from one shot while the energy from the subsequent shot was propagating through the water column. This enabled data to be acquired down to nine seconds in the deepwater area, even with a short (18.75 m) shotpoint interval. By only overlapping the data through the water column, the only interference from the following shot was the direct arrival of energy, which is readily removed in data processing.

Operational challenges

The survey presented significant operational challenges due to its location in a busy producing field, and a portion of the area lying in shallow water, with limited sea space to turn. A number of obstructions resulted in large exclusion zones in the south of the area, meaning that part of the survey could not be acquired as initially envisaged. In order to acquire data in the priority areas to the south east of the survey, with maximum offset and azimuth coverage in these locations, while maintaining a safe distance from the FPSO's and drilling rigs, it was necessary to alter both the spread configuration and shooting direction in this area.

Imaging

A fully integrated reservoir-oriented processing sequence was recently performed on this dataset. The initial processing included shallow water demultiple, broadband 3D SRME, high-resolution Radon demultiple and phase-only Q-compensation. 3D common-offset vector binning was performed and the data regularized and interpolated on to a 12.5 x 25 m grid. The parallel reservoir processing flow included seismic rock property analysis, well-to-seismic ties (on the fast-track data) and modelling of synthetic gathers to match with the processing. Preliminary imaging results show considerable improvement over the previous data for this area, with the new data showing higher definition in the shallow section, better fault planes and better deep penetration.

Final seismic data volumes will include both time and depth migrations and the reservoir products will include acoustic, stochastic and azimuthal inversion products to provide a detailed analysis of the reservoir for the derivation of high-quality reservoir models and production scenarios.

Subsalt imaging through full-azimuth broadband acquisition with ultra-long offset – Ibalt, Deux and Trois in the US Gulf of Mexico

Survey design

The image quality of many early WAZ configurations was constrained by the limited offsets acquired (typically 6 km to 8 km). Studies of certain areas in the US Gulf of Mexico indicated that further improvements to the image could be achieved by improving the azimuth distribution and extending the offset range beyond the limits imposed by the physical constraints of the recording equipment, (Cvetkovic et al., 2011; Mandroux et al., 2013). The benefits of doing this would include improved illumination, more accurate high-resolution velocity models, (enhanced by full waveform inversion), and reduced contamination of the signal from multiple energy.

The challenge was to design a configuration that would combine improvements in azimuth distribution, offsets exceeding 18 km, compatibility with variable-depth streamer broadband acquisition and data with regular and consistent fold, offset and azimuth distribution from bin to bin. This had to be achieved while minimizing redundant low-fold coverage and excessive vessel time spent during line changes. The design adopted consisted of a five-vessel configuration – two multi-streamer, single-source vessels and three additional source vessels (Figure 1), with the vessels being staggered in the inline direction.

Acquisition was to be carried out antiparallel and orthogonal with the relative positions of the vessels being different for each sail line direction, providing a variety of azimuth directions in the super-shot gather, and taking advantage of the reciprocity principle to maximize azimuth distribution.

Operational challenges

CGG has used this technique to acquire three multi-client surveys in the Gulf of Mexico: IBALT (Integrated BroadSeis Acquisition and Long Tow), IBALT Deux (acquired between July 2012 and October 2013) and Trois (acquired between April 2014 and October 2014). Each streamer vessel towed 10 x 9 km streamers at a separation of 120 m, providing an overall spread of 18 km x 6 km. The staggered geometry provided four axes of very long offsets, up to 18 km, and full-azimuth (FAZ) distribution (assuming source-receiver reciprocity) up to 9 km (Mandroux et al., 2013).

The main challenge anticipated for the staggered acquisition configuration was turning the whole five-vessel fleet at the end of each sail line in a safe and efficient manner, and lining the fleet up in the appropriate configuration for commencement of the subsequent line. However, the staggered technique proved to be an advantage in that each vessel can start to turn in succession, as soon as it no longer contributes to the full fold area, while the vessels behind are still completing their production line. This allows acquisition in swathes without the lengthy turns required to maintain safe distances between vessels when they are aligned. As a result, there have been significant improvements in efficiency, with reduced line-change times achieved since the start of this acquisition configuration when compared with some other conventional WAZ configurations.

This efficiency in operations has been successfully maintained for its two-and-a-half-year duration. The only significant reduction has occurred during periods where other adjacent seismic acquisition programmes have necessitated the use of time-share, to minimize the impact of seismic interference.

Imaging

This staggered acquisition technique has significantly improved our ability to image subsalt structures. Ultra-long offset RTM 3D angle gathers have large incident angles, containing valuable information for residual curvature analysis to aid the subsalt velocity update for features such as steeply dipping salt flanks and subsalt three-way closures. When compared with velocity modelling excluding the ultra-long offsets, a better subsalt structure and flatter gathers were revealed. In addition, the tomography velocities closely matched the sonic log at the well location (Figure 2) (Wang et al., 2014).

The full azimuths and ultra-long offsets combined with variable-depth streamers have shown benefits in bandwidth extension, multiple suppression (Yu et al., 2013), velocity model building (Mothi et al., 2013; Wu et al., 2013) (Figures 3 and 4) and improved subsalt illumination (Wu and Li,

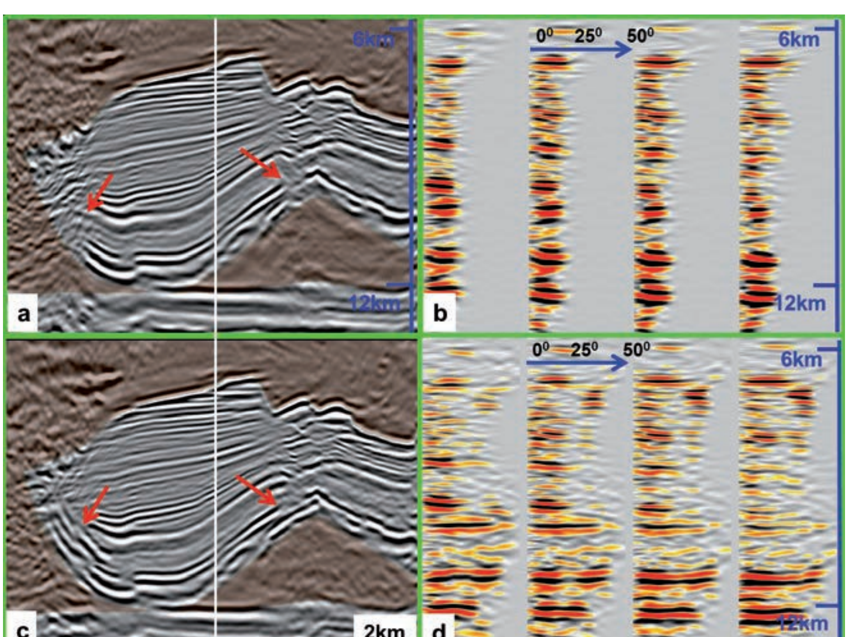

Figure 2 *Long offsets improve velocity modelling for flatter gathers.*

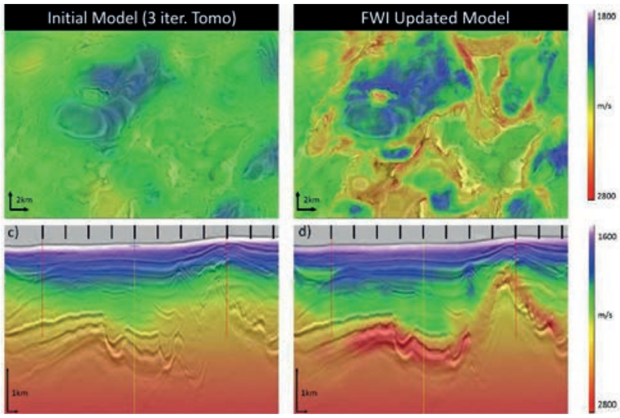

Figure 3 *Low frequencies and long offsets are ideal for FWI (Full Waveform Inversion).*

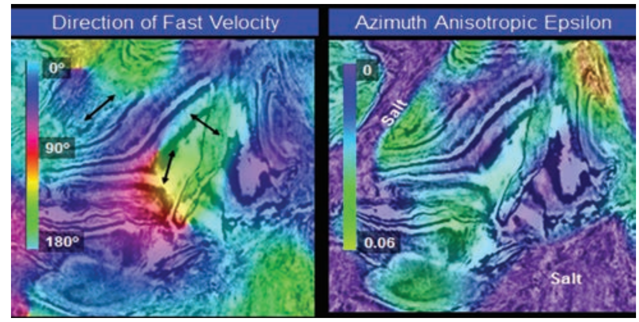

Figure 4 *Full-azimuth data provides excellent models for tilted orthorhombic imaging.*

2014) (Figure 5). At the same time, the large variations in take-off angles create challenges for deghosting, which is important for seismic processing, especially for 3D surface-related multiple elimination (SRME) and improving bandwidth and resolution. Wang et al. (2013), proposed a pre-migration deghosting method using a bootstrap approach in the Tau-P domain, which is effective for most 2D and 3D data in NAZ or WAZ acquisition geometries. However, for data with large azimuths and take-off angles of ghosts, the wavefield is strongly 3D. Wang et al. (2014), proposed a 3D deghosting method for hydrophone-only data, which is fully data-driven and uses a progressive sparse Tau-P inversion to perform 3D joint deghosting and crossline interpolation in one step. By applying this 3D deghosting to full-azimuth data, the better ghost removal improved the seismic images and provided better multiple suppression from 3D SRME.

To show the benefit of 3D deghosting, Wu (2014) performed Kirchhoff sediment flood migrations using the side-gun data before deghosting, after bootstrap deghosting, and after 3D deghosting. Figures 6a and 6d show a depth slice and a cross-section using the data before deghosting. The primary and ghost energy are both present in the migrated image. The Top of Salt (TOS) is not clearly defined in the depth slice due to the interference of primary and ghost energy. Figures 6b and 6e show the same depth slice and cross-section after bootstrap deghosting, and then Figures 6c and 6f show the migrated images with the data after 3D deghosting where the TOS event is more coherent in both the depth slice and cross-section.

High-density broadband full-azimuth acquisition: West Africa

Survey design

The West Africa Atlantic margin is known for its complex subsalt geology characterized by extensive salt bodies and dipping seismic reflectors. To meet the requirements for the prospect, a tailored acquisition design was required to improve imaging of reservoirs in the deep Oligocene and Cretaceous subsalt structures. A high-density broadband dataset was needed in combination with WAZ sampling, with strong low-frequency energy necessary to image the deep target, and a broad bandwidth to provide high-resolution imaging above the salt.

An earlier WAZ design, used in the Gulf of Mexico (Threadgold et al., 2006) and West Africa (Saint Andre et

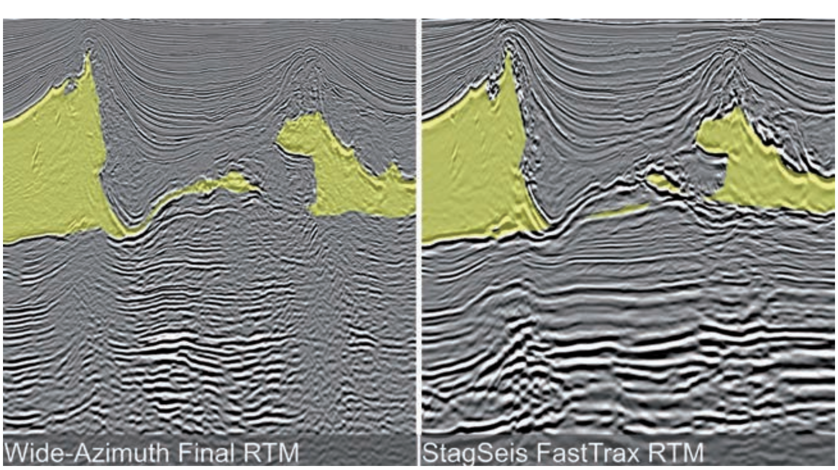

Figure 5 *Full azimuths and long offsets deliver improved subsalt illumination.*

al., 2010), was initially considered as a potential solution. However, a new configuration was designed for this area considering the introduction of the variable-depth broadband solution.

This new design (Landais et al., 2014), involving a multi-vessel and multi-pass configuration, was adopted. Consisting of one streamer/source vessel and two additional source vessels, with all vessels deploying two sources, the acquisition of a survey line was completed by the combination of three successive acquisition passes on one heading, with offsets up to 8 km provided by the long streamers. Combining these sail line passes on 2 x 2 headings enabled a full-azimuth distribution within a 6-km radius (Figure 7) to be obtained and provided high spatial resolution compared with many other WAZ configurations, yielding a bin size of 6.25 m x 25 m with a combined fold of 446. The shot interval was 100 m inline and 50 m crossline.

This design provided the dense wide-azimuth data needed for the prospect, compatible with the variable-depth streamer configuration, and giving a higher proportion of data at near offsets, allowing more effective demultiple to be achieved. The new design also freed up more time for source maintenance, because for each sail line (consisting of three passes), the streamer vessel would make two passes without using her source, and one source vessel was not required for one of the passes.

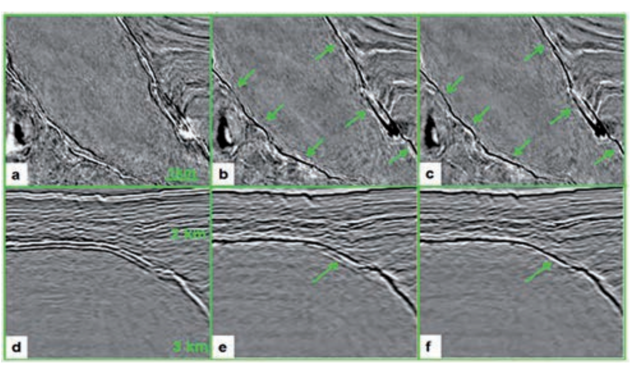

Figure 6 *Kirchhoff migration stack depth slice with input data (a) before deghosting, (b) after bootstrap deghosting, and (c) after 3D deghosting. Kirchhoff migration stack cross-section with input data (d) before deghosting, (e) after bootstrap deghosting, and (f) after 3D deghosting.*

Operational challenges

The main challenges encountered were heavy barnacle growth on the streamers, particularly in the early acquisition phase, and some streamer damage caused by Fish Aggregating Devices (FAD) drifting into the prospect from time to time. Streamer cleaning and FAD clearing programmes were set up and run during the acquisition to minimize the impact of these factors on the operation.

The survey was recently completed with no downtime caused by adverse weather conditions and generally low levels of noise were recorded throughout the acquisition.

Imaging

Imaging is currently underway for this project. Fast-track processing was completed within three and a half month months of the last acquired shot. This fast-track PSDM sequence was started on board the streamer vessel during acquisition, with early steps in the flow (principally de-noise, de-signature and de-ghosting and de-multiple) run on board, and the data then taken to CGG's data processing centre in Crawley for completion of the imaging steps.

A complex multiple wavefield was anticipated – the water bottom topography was known to be rugose, with depths varying from 1500 m to 2500 m. It was therefore decided that a wavefield modelling approach to multiple attenuation would yield optimum results, considering the complexity of the water bottom topography and the tight time frame available for the fast track. This wavefield modelling approach involves the propagation of the recorded wavefield within a reflectivity model in order to predict the associated multiples. The reflectivity model was derived from a 2007 PSTM vintage data volume of the prospect. The wavefield modelling (Pica et al., 2005) is demanding on computational resources and required installation of the latest generation of processing hardware on the vessel. This demultiple approach offered significant operational efficiency advantages to the data acquisition over

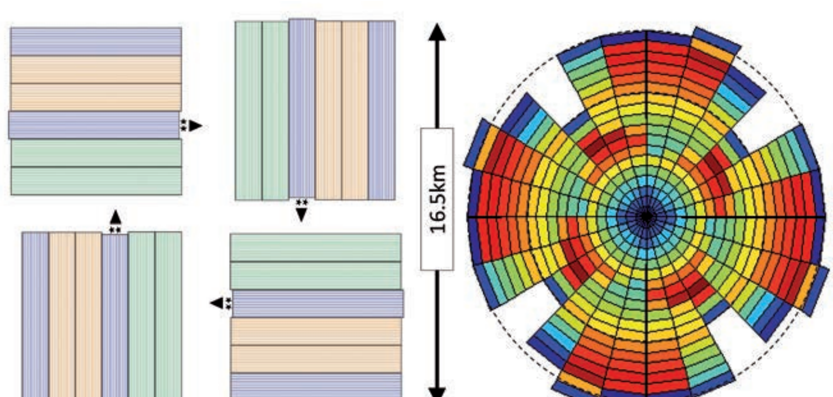

Figure 7 *West Africa illumination – multi-pass acquisition on four headings leading to the full-azimuth and offset distribution contained within the super shot-gather.*

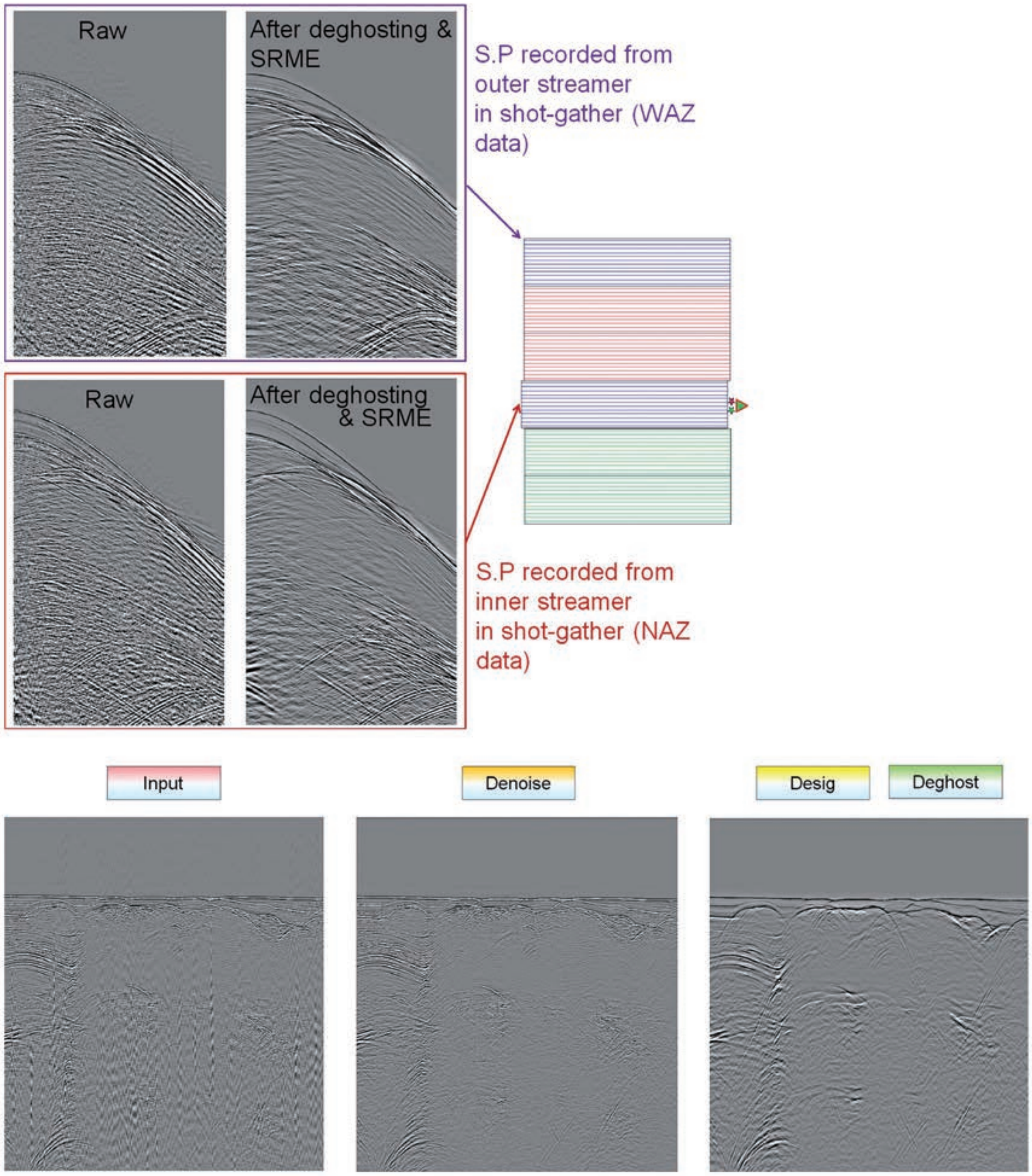

Figure 8 *West Africa fast-track: promising early fast-track results from sail line shot and stack sections indicating strong imaging potential.*

alternative convolutional methods as it does not necessitate forcing the completion of an acquisition swath of data before application of the process can start.

Initial fast-track results (Figure 8) have been extremely encouraging both in terms of raw data quality, and with respect to the de-noise, deghosting and demultiple steps.

Conclusion

To improve the image of complex geology demands an acquisition design that respects the anticipated imaging challenges. Broadband recording and increased spatial sampling can improve the resolution of sedimentary layers and can lead to improved facies discrimination and high-resolution tomography. Low-frequency strength and ultra-long offsets can contribute to subsalt penetration and provide better definition of overburden velocities as a result of FWI. High signal-to-noise ratio, particularly at low frequencies, provided by quiet solid streamers, stabilizes inversions for reservoir characterization purposes. Increased azimuth content brings better illumination as well as facilitating improved multiple attenuation, and also leads to better constraints on anisotropy.

Therefore, design improvements are achievable requirements over a 'one-design-fits-all' solution. Each area comes with its own unique set of challenges and requires a survey design that is optimized to meet these. The design stage is fundamentally important and an integrated approach that incorporates an assessment of the illumination, bandwidth and spatial sampling needs, together with the operational constraints, and then the subsequent processing and reservoir characterization requirements, leads to the most efficient solution for each particular case. Also, experience and expertise in the operation of multi-vessel acquisitions are essential to ensure safe and efficient project execution.

The three case studies confirm that an optimized design leads to significant improvements. In Central America, there is improvement resulting from the high-density and broadband design with the new data showing higher definition in the shallow section, better fault planes and better deep penetration. In the US, the full azimuths and ultra-long offsets combined with variable-depth streamers have shown benefits in bandwidth extension, multiple suppression, velocity model building, and improved subsalt illumination. In West Africa, where acquisition was very recently completed and results are not yet available, initial raw data quality is excellent and fast-track images are hinting at strong imaging potential.

There is a saying that 'the whole is greater than the sum of its parts'. An insight into this underlying principle may lead to the consideration that investments already made on existing NAZ 3D and/or vintage WAZ acquisitions may yield further return by supplementing and combining this existing data with future acquisition to provide additional azimuth and offset coverage. If the saying holds true, there is still room in the currently suppressed exploration conditions to find ways of obtaining more for less.

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