Dual-sensor towed streamer: from concept to fleet-wide technology platform

Martin Widmaier[1*], Eivind Fromyr[1] and Volker Dirks[1] discuss the lessons learnt from the roll out of dual-sensor technology in PGS' fleet.

The launch of the dual-sensor towed streamer technology in 2007 is seen by many in the industry as the most important milestone in marine seismic technology in the last decade. The introduction of the technology triggered a significant interest and demand for broader bandwidth seismic data and increased the industry-wide awareness of the geophysical benefits of such broadband data for both frontier exploration and production monitoring in mature basins. It also resulted in the rapid development of new acquisition and processing technology, both concerning the source and receiver side, as well as changes to seismic vessel design and equipment. The geophysical benefits of broadband data and the availability of up- and down-going wavefields as part of the dual-sensor deghosting methodology are now routinely exploited throughout the entire seismic value chain, including seismic imaging and reservoir characterization.

After the first 2D dual-sensor survey in 2007, which was quickly followed by the first 3D acquisition commencing on New Year's Eve 2008, PGS has steadily converted its seismic fleet from hydrophone-only to dual-sensor streamers. The pace of the technology roll-out has been largely driven by the life-cycle of existing streamer inventory and the equipment needs for newly launched seismic vessels as part of an ongoing fleet renewal process. The fleet-wide roll-out of dual-sensor technology will finally be completed in the 4th quarter of 2015 with the upgrade of the last Ramform vessel. Given the scale and complexity of replacing and industrializing a complete acquisition platform, there have naturally been significant lessons, some of which we will be sharing in this article. We will also discuss some of the acquisition and processing technologies that have been developed and/or adapted in order to fully utilise this new marine seismic technology platform.

Robust ghost removal for deeper streamer tow

To be successful in today's challenging E&P environment, petroleum geoscientists must detect and properly image increasingly complex reservoirs by resolving the fine detail of ever smaller hydrocarbon accumulations. High quality seismic data plays a key role in this task and is of great significance in the effort to reduce overall E&P risk. The demands placed on modern seismic data are multifold, but critically the data needs to enable the identification and delineation of leads/prospects based on pre-stack seismic and to quantify key reservoir properties to increase the probability of successfully separating lithology-fluid facies. All of these goals must be achieved in 3D using all the dimensions of the seismic data, mainly pre-stack, and later on 4D (time-lapse). It has been well understood for some time that data richer in both low and high frequency information would form the optimum input for improved reservoir delineation and high-resolution imaging and that improvements in the signal-to-noise ratio of the recorded data could be made by towing the seismic equipment deeper.

Traditionally, streamer tow depths have been limited to between 7 m and 10 m to avoid attenuation of high frequency content by the so called ghosting effect. Ghost notches are created when a range of frequencies are attenuated through destructive interference between seismic energy directly reflected from the subsurface and ghost reflections of the same energy reflected at the sea surface directly above the source or receiver equipment.

The introduction of dual-/multi-component streamers has enabled the industry to overcome the fundamental receiver ghost problem (Carlson et al., 2007; Caprioli et al., 2012). The removal of the receiver ghost increases the seismic bandwidth and thus provides better resolution for interpretation (Figure 1). The ability to remove the ghost accurately allows the streamers to be towed deeper. The signal-to-noise ratio is improved by deeper tow, especially at the low frequency end of the seismic bandwidth. Improved low frequency content enhances the quality and accuracy of seismic inversion and reservoir characterization (Kroode et al., 2013).

For current dual-sensor and multi-component streamers, the overall signal-to-noise ratio (S/N) of the separated wavefields is improved, if particle motion sensor data are not used for lower frequencies (typically below 15-20 Hz, Day et al., 2013; Caprioli et al., 2012; Carlson et al., 2007). Particle motion sensors in towed streamers record relatively high levels of low-frequency mechanical noise. In order to

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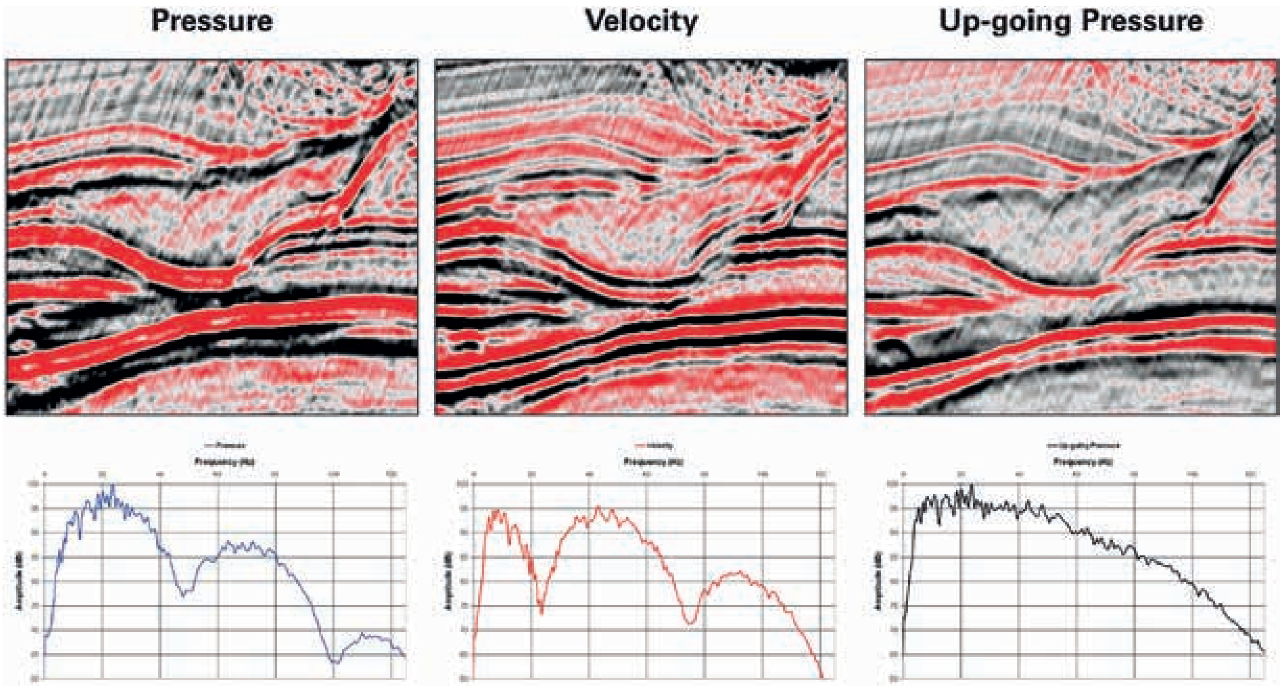

Figure 1 Unmigrated stack comparison as shown in Carlson et al (2007). Note the complementary amplitude spectra for pressure vs. particle velocity. The images are from left to right, the pressure only result, the vertical particle velocity (or particle motion) only result and the up-going (de-ghosted) pressure wavefield derived from the pressure and velocity wavefields. The data shown in the example was acquired in 2007 with a streamer depth of 15 m.

overcome the lack of particle motion signal with good signal-to-noise ratio at the low frequency end, high-quality deep tow pressure recordings are utilized.

Safe and efficient operations with new generation seismic vessels

There are three key elements that are vital to achieve industry-leading efficient marine seismic acquisition: 1) The number of deployable streamers; 2) the speed at which a large 3D spread can be deployed and towed; and 3) the amount of down-time due to unacceptable weather conditions. The Ramform Titan class design is optimized with respect to these critical factors.

The ability to increase the effective tow depth by utilizing the dual-sensor acquisition platform has opened up the possibility of acquiring seismic data in weather conditions for which traditional shallow-tow surveys would have had to be suspended due to the significant swell noise created by the increased wave action. This operational benefit was demonstrated on one of the very first dual-sensor 3D surveys when a traditional acquisition survey was being performed close by during the same time period; the weather related standby for the traditional acquisition survey was 24% compared to 4% for the dual-sensor survey. However, it was quickly realized that although high-quality data could now have been recorded in much more marginal weather conditions, operational safety considerations and the well-being of the crew became the limiting factors.

All the lessons from operating in challenging weather conditions enabled by dual-sensor technology have been incorporated in the design of the latest Titan-class vessels. The first two vessels of this new generation of purpose-built seismic boats, the *Ramform Titan* and *Ramform Atlas*, have been launched in 2013 and 2014 respectively (Figure 2). In order to make these vessels more efficient yet allow safe and reliable operation with minimal weather related down-time, the stern of the vessel was dramatically widened to 70 m. Not only does this design allow for up to 24 streamers to be towed simultaneously but it has also resulted in the vessel movement at the stern being significantly reduced, thus minimizing wave induced tug noise. The ships roll decay rate has been significantly improved allowing the vessels to operate in more marginal weather yet recording high-quality data.

Larger deflector doors enable spread widths of up to 1700 m, which means that up to 18 streamers can be towed at a 100 m streamer separation. In high-density 3D streamer mode (HD3D), with reduced cable spacing, even more streamers can be deployed. The vessel's diesel electric power plant of six units of 3820 kW each provides the triple propellers with enough power to tow these huge spreads comfortably.

The significantly larger back deck allows for very efficient streamer deployment and retrieval. Multiple streamers can be deployed or picked up at the same time without sacrificing safety. Maintaining and servicing large streamer spreads also means that one needs to have access to the in-sea equipment in a safe and efficient way. The size and shape of the Titan class vessel has enabled the two workboats to be located at the stern, where wave motion is at its smallest, allowing for safe deployment and retrieval in cradles with minimum human exposure. To achieve greater operational efficiency, the Titan class is bigger than any other seismic vessel. The increased space and the comfort that comes with it creates better conditions for team work and interaction and therefore further improves efficiency and safety. Working offshore becomes more similar to working in office locations onshore.

Flexible and dynamic tow depth configurations

As mentioned previously, the weather impact on data quality can be further reduced by towing the dual-sensor streamer deeper. While deeper tow enables the recording of more low-frequency signal energy, it can increase operational complexity at the same time. Increasing and maintaining deeper streamer front-ends in a 3D spread is challenging. Deeper front ends typically require additional downward forces and create higher drag. In the early days of the dual-sensor technology roll-out, these downward forces were generated with tailor-made weights. The same effect is now being achieved by using scalable depressor wings.

Since the wavefield separation for dual-sensor and multi-component streamers is based on recordings from collocated complementary sensors, there is no theoretical requirement to tow the streamer flat. The de-ghosting process is geophysically robust even in the presence of uncontrolled or indeed controlled cable depth variations. The up-going and down-going wavefields generated during the de-ghosting process can simply be re-combined to generate the total pressure field at any chosen flat datum.

Thus streamer depth profiles can be designed and deployed in order to optimize seismic data quality without sacrificing acquisition efficiency. This means a nominal tow depth of between 25 m and 30 m can be achieved without pushing the front-ends beyond depths that have been routinely deployed for dual-sensor streamers in the past (15 m-20 m). Streamer steering devices can be utilized to slightly increase the tow depth over the near offset range until the nominal tow depth is reached (Lesnes et al., 2014). Similarly, the operationally challenging deep tow of very wide streamer spreads can be facilitated by relaxing slightly the front-end tow depths for the outermost cables compared to the centre cables without sacrificing geophysical integrity.

The combination of dual-sensor/multi-component streamers with modern depth steering devices has also enabled the rapid adjustment of tow depths during ongoing surveys without negatively impacting data quality and without complicating subsequent signal processing and imaging procedures. The need to alter the tow depth could be triggered by noise issues (e.g., strong swell, barnacle growth), shallow obstacles (e.g., pipelines, fishing traps), or other local conditions such as currents and thermoclines. The dual-sensor wavefield separation process handles depth changes implicitly and automatically. Given the insensitivity of the dual-sensor wavefield separation to tow depth variations, the traditional industry standards for streamer depth tolerances set to +/- 1 m can be significantly relaxed for multi-sensor streamers.

Figure 2 Ramform Atlas photographed while working in the North Sea. The 70 m wide back deck allows safe and efficient deployment and retrieval of a high number of streamers. Note also the calm sea behind the vessel where the two workboats are deployed in cradles.

Time-lapse (4D) monitoring

An important milestone for the industrialisation of dual-sensor towed streamer technology was the demonstration of the technology's 4D pre-stack and post-stack compliance. One of the 4D repeatability requirements for traditional hydrophone-only marine streamer seismic is to be able to repeat the acquisition configuration as much as possible. In particular, the streamer tow depth of a monitor survey is required to be the same as in the corresponding base survey. For dual-sensor or multi-component streamers however this tow depth requirement can be relaxed. The collocated dual-sensors allow the seismic wavefield to be separated into up- and down-going parts. These may then be independently redatumed and summed (re-ghosted) to emulate the total pressure wavefield as recorded by conventional acquisition systems at any recording depth. This reconstruction process treats the amplitude and phase of the seismic signal correctly. Thus, the dual-sensor or multi-component streamers may be towed at any depth also in a 4D context. The deeper tow depth compared to what has been used for conventional 4D acquisition surveys then takes advantage of the quieter recording environment and increases the bandwidth of the data. This fundamental benefit as well as 4D backward compatibility were validated in a very early field trial in 2009 (Day et al., 2010).

As the reconstruction of hydrophone-only data reintroduces the receiver ghost, the broadband uplift is commonly sacrificed in order to maximize backward compatibility and repeatability. The 4D dual-sensor data acquired so far has therefore commonly been utilised in a two- or even three-fold approach: the reconstructed and re-ghosted data has been used for 4D monitoring purposes, and the full broadband up-going wavefield (P-UP) has been the basis for high-resolution imaging as well as for quantitative interpretation (e.g., seismic inversion). The full benefit of the increased bandwidth for 4D projects will only be realized when both baseline and monitor surveys are acquired with advanced streamer technology that enables full integrity and 4D-friendly wavefield separation.

Since the original 4D validation test in 2009, 17 proprietary dual-sensor base line and monitor surveys have been acquired to date. With time lapse, reservoir characterization, and high-resolution imaging objectives in mind, all the 4D acquisition projects made use of deep tow and so-called high-density spreads. The majority of these surveys were acquired with 50m streamer separation and with up to 16 treamers deployed.

Impact of the rough sea surface

Wavefield separation based on de-ghosting of dual-sensor data allows us to look at the ghost wavefield independent of the primary reflection wavefield (Figure 3). The imprint of the rough sea surfaces can be clearly observed in the ghost wavefield when separated. Naturally, the same complex sea surface reflections are also present in the original hydrophone recordings of the total pressure field. Such sea state imprints can negatively affect the repeatability requirements for 4D seismic as the effects of a rough sea surface are highly variable spatially during a given survey and between successive acquisitions. Acquisition based de-ghosting methods represent the most robust way of minimizing 4D noise by adequately removing the non-repeatable sea-surface effects, and therefore improving the repeatability of subsequent seismic surveys.

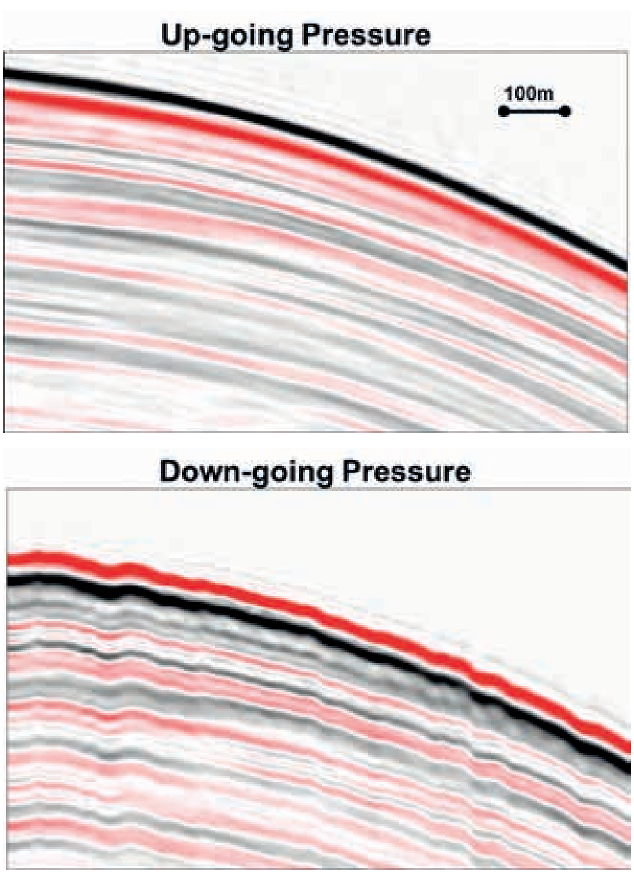

Figure 3 *A receiver ghost is the result of an up-going wavefield (top) being reflected downwards at the sea surface. The ghost reflections, i.e., the down-going wavefield (bottom), carry an imprint of the sea surface shape above the streamer at the time of the seismic recording. Imprints of rough sea surfaces on the ghost reflections can be clearly observed. The example is a shot gather from offshore Brazil (Burren et al., 2013).*

Noise mitigation strategies

The integration of particle motion sensors (either particle velocity sensors or accelerometers) into a seismic streamer has led to new requirements for noise mitigation and onboard QC. Particle motion sensors are more sensitive to mechanical vibrations and turbulence along or in the vicinity of the streamer compared to pressure sensors (hydrophones). Peripheral units such as steering devices, acoustic pingers, compasses and retrievers which are traditionally attached to seismic streamers can cause undesirable vibrations and turbulence affecting the quality of the recorded motion sensor data.

Based on the experience of recording dual-sensor data for over seven years such ‘attached’ devices have been re-engineered to minimize vibration and mechanical noise. The new devices are now physically integrated in the streamer through connector units (Hillesund et al., 2012).

Seismic operations in temperate waters such as, for example, offshore West Africa or Brazil, are exposed to barnacle growth on any in-sea equipment including seismic streamers. Streamer drag as a result of barnacle infestation will increase significantly, potentially impacting streamer separation and resulting in higher fuel consumption. In the worst case, uncontrolled barnacle growth can result in equipment failure, breaking or tangling of the streamers.

Barnacle growth also generates undesirable noise. Historically, manual cable cleaning and scraping has been very often the only effective measure to mitigate barnacle-related problems. In recent years, however, automated in-sea streamer cleaning units (SCU) have been engineered, allowing for continuous proactive barnacle removal (Figure 4). The cleaning units are deployed at the streamer front and retrieved at the streamer tail. The devices are powered by the movement of the seawater relative to the streamers and are designed to pass devices such as birds and acoustic units without further human interaction. These cleaning devices are nowadays also operated while recording of seismic data is ongoing.

On-board workflows for quality control have been extended to monitor not only the noise levels of hydrophone

Figure 4 *Automated in-sea Streamer Cleaning Units (SCU) have been engineered to allow for continuous proactive barnacle removal during ongoing operation.*

recordings but also the quality of the particle motion data and data deliverables like the up-going wavefields (i.e., wavefield separated/de-ghosted data). Ambient noise guidelines have been adapted to the new technology. For conventional shallow tow hydrophone-only streamer acquisition, the weather is usually the limiting factor. Lines affected by strong weather noise are rejected (or accepted) based on noise level criteria. For dual-sensor acquisition, line-to-line variations due to weather practically do not exist anymore as the entire streamer spread is towed below the base of the waves. Noise levels are predominantly driven by the towing noise, streamer peripherals (e.g., attached devices, barnacle growth) and the speed of the vessel relative to the water. Modern real-time quality control systems have been implemented over the past few years on all vessels to enable the seismic crew to monitor noise levels together with the actual production speed of the vessel. After the data has been acquired, noise removal algorithms and the wavefield separation process itself can eliminate noise from the raw dual-sensor data and from the ghost-free up-going wavefield (P-UP). The wavefield separation processing is usually done on-board while a survey is in progress.

Streamer fanning and infill management

Streamer fanning is the term used to describe the ability to increase the streamer separation in a marine seismic acquisition spread, progressively from the head to the tail. The resulting streamer spread has a fan-like appearance when viewed from above. Fanning aims to improve and evenly distribute coverage at the far offsets, without compromising seismic data resolution or quality. Ultimately, streamer fanning increases the acquisition efficiency by reducing infill.

The streamer fanning concept requires lateral steering devices. With the roll-out of integrated bird technology, streamer fanning has become a viable option for most of the 3D dual-sensor towed streamer vessels, and it is now the default mode for multi-client operations. Recent surveys report infill reductions in the order of 3-5 percentage points. In parallel, and with modern broadband data quality

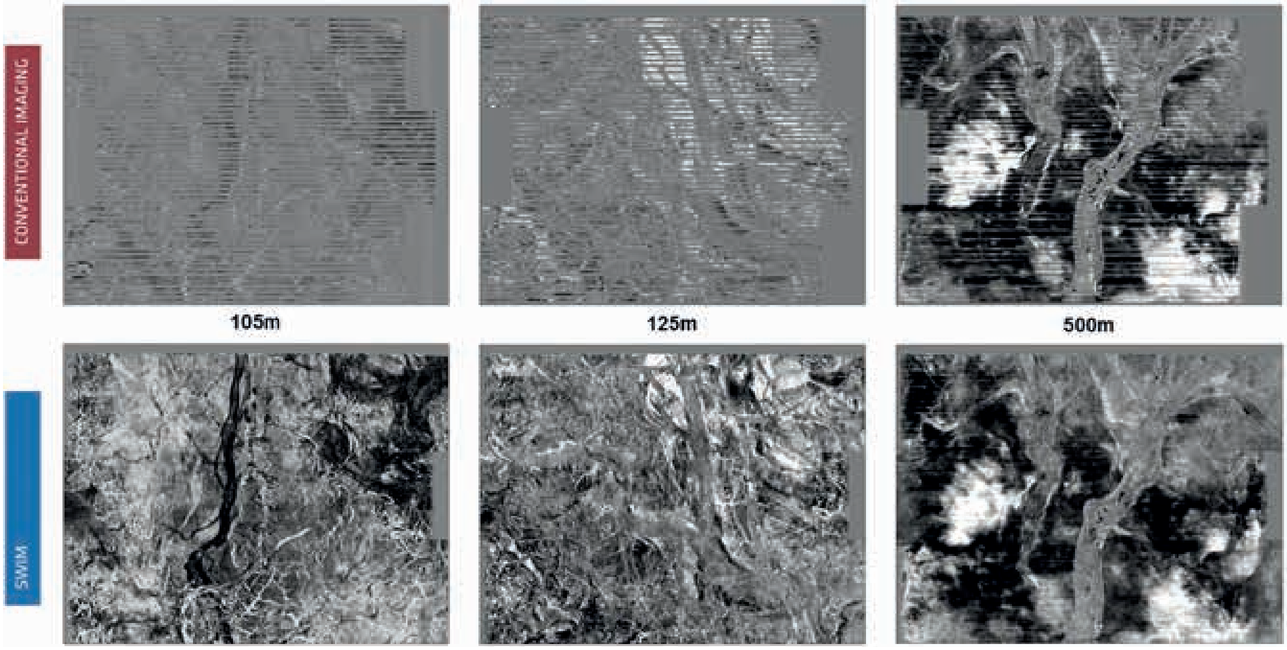

Figure 5 *Shallow subsurface images at depths of 105 m, 125 m and 500 m in water with a depth of 70 m offshore Malaysia. The top image using primary reflection arrivals only shows a strong imprint of the sail line geometry, whereas the separated wavefield image at the bottom, using the additional illumination provided by the sea-surface reflected down-going wavefield, shows a seamless and complete image of the complex multiple channel systems.*

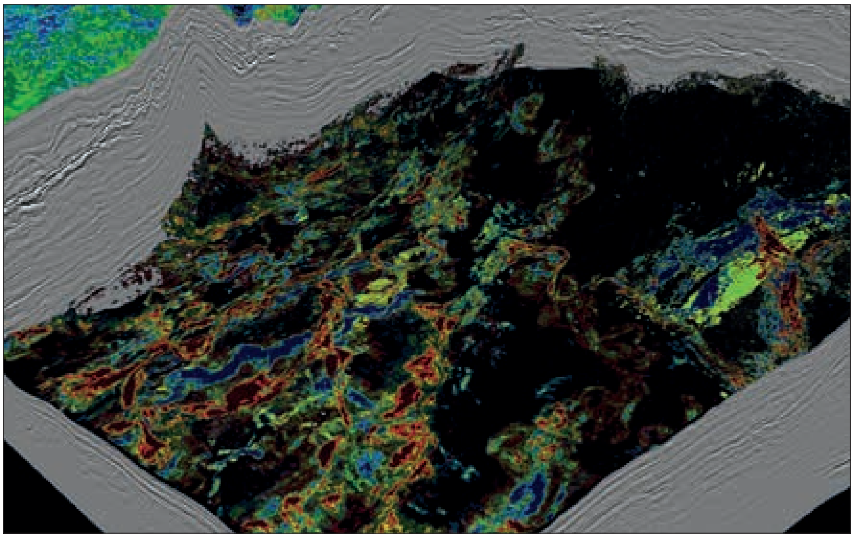

***Figure 6** Deep Cenomanian/Turonian channel sands revealed by dual-sensor data offshore Ivory Coast, West Africa. Separate lithological intervals are identified in the 3D seismic cube by pre-stack relative acoustic impedance inversion and highlighted in different colours from light green for the deepest to dark red colours for the shallowest units.*

requirements in mind, the traditional flex-binning related coverage specifications have been replaced by infill specifications and coverage QC that are based on geophysical and survey dependent criteria (Day and Rekdal, 2005).

Improving near-surface imaging

3D towed streamer acquisition in shallow water can lead to illumination holes at swath boundaries due to a lack of near offset data. The missing near offset data not only creates a footprint in the shallow image, but also limits the ability to quality control migration velocities based on flatness of the gathers. The ability to conduct AVO/AVA type studies is limited by the same effect. It has been demonstrated that the concept of virtual source imaging (Wapenaar et al, 2010) can be extended to multi-sensor streamer acquisition to utilize sea surface reflected downgoing wavefield energy that provides the missing near-surface information. Recent case studies (e.g., Long et al., 2013 and Rønholt et al., 2014), demonstrate how separated wavefield imaging from dual-sensor systems can be used to remove acquisition footprints and shallow coverage gaps that are evident if only the primary reflections are used (Figure 5). The shallow overburden can not only be imaged seamlessly, but also complemented by AVO/AVA analysis facilitated by the virtual source concept. Imaging with separated wavefields can also be a driver for acquisition efficiency. The traditional survey planning considerations for maximum spread width and thus sail-line separation are based on primary reflections only and may thus be relaxed by taking sea surface reflected downgoing wavefield energy into account.

Rock property estimation

Dual-sensor data has been successfully used for pre-stack analysis in a multitude of geological settings with the aim of deriving reliable rock physics attributes (Figure 6). These studies have demonstrated that the richer content of pre-stack compliant low-frequency information in dual-sensor data allows for the accurate prediction of lithology-fluid distribution and even porosity using a robust quantitative interpretation workflow (Reiser et al., 2015). The accuracy of the rock property prediction has been demonstrated using blind-well analysis establishing dual-sensor data as a valuable asset for de-risking leads and prospects through improved reservoir characterization in areas of limited well control.

Conclusions

The dual-sensor marine towed streamer technology has provided a step change in seismic data quality since 2007. The increase of the natural frequency content of the recorded seismic data as well as the ability to accurately decompose the seismic data into up- and down-going wavefields has resulted in benefits throughout the entire seismic value chain. Access to all recorded wavefields has resulted in the ability to improve the image quality of the near surface in shallow water environments. The richer content of reliable low-frequency information has been successfully used to predict rock properties away from well control, enabling improved de-risking of leads and prospects in early exploration settings.

Finally, the multi-year rollout of this new marine seismic streamer technology has resulted in numerous improvements to seismic acquisition technology and operational procedures and has offered greater flexibility for survey design and seismic operations. Data quality objectives have been successfully combined with the requirements for safe and efficient operations.

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