NEW SEISMIC ACQUISITION TECHNOLOGY FOR EFFICIENT SUBSALT AND PRE-SALT OIL EXPLORATION

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Abstract

Successful sub-salt exploration requires seismic data with good broadband characteristics, plus rich azimuths and offsets. Economic pressures also place a renewed emphasis on cost effective exploration. In this paper we describe a new multimeasurement towed-streamer acquisition technology which could be beneficial for subsalt and pre-salt reservoir exploration.

Multimeasurement technology offers high-resolution imaging of shallow sediments. Combining with rich azimuth acquisition designs, such as WAZ, improves illumination of deeper targets. In complex geologic environments this generates significant energy propagating in the cross-cable direction. Field data from the multimeasurement technology deployed in a WAZ geometry demonstrate that the wavefield reconstruction process performs well under these conditions.

Multimeasurement wavefield reconstruction also offers opportunities to acquire data more efficiently. Wide streamer and wide source configurations provide an efficiency uplift, and rely on the wavefield reconstruction to maintain the desired cross-cable sampling in the shot domain. A dual vessel configuration provides greater efficiency, generating twice the subsurface coverage with a single streamer vessel by adding a source vessel.

Introduction

Many developments in marine acquisition technology in the last decade were triggered by the challenges faced by the oil industry in exploration and development of subsalt and pre-salt oil reservoirs. Examples include full azimuth acquisition geometries for sub-salt illumination, and broadband acquisition and/or processing methods to maximize the useable seismic bandwidth (including low frequencies for sub-salt penetration).

More recently, difficult economic conditions have forced a renewed focus on controlling cost across the E&P cycle. This in turn has driven further innovations in marine acquisition technology and techniques. These methods aim to maximize the subsurface coverage obtained by each pass of the seismic vessel, optimizing asset utilization, and reducing the cost per square km – whilst maintaining the geophysical attributes and quality necessary to meet the survey objectives.

In the case of sub-salt exploration, such as encountered offshore Brazil, a blend of both approaches is needed. Successful solutions must span acquisition, processing and interpretation. Technical challenges focus on the need for high-quality seismic data to allow good understanding of geology from seafloor to target - so as well as providing an image of the drilling targets the seismic is required to deliver reliable information about the overburden to mitigate drilling surprises. Economic challenges reflect the need to acquire data over large areas in a cost-effective manner, but without compromising data quality.

In this paper we review a new class of marine seismic technology, well-positioned to improve sub-salt exploration success. We outline a range of strategies to acquire data faster, more cost effectively, and with less operational and environmental exposure.

Increasing efficiency with conventional technology

The area of the sub-surface covered by a single pass of a seismic vessel can be thought of as a seismic "paintbrush." The wider the paintbrush the more efficient acquisition becomes. One way to achieve this is by simply increasing the separation between streamers. However this also increases the cross-cable cmp bin size, which may compromise image quality – particularly in areas of complex geology with steep dips, high frequency content and strong velocity contrasts. Alternatively, the streamer separation is maintained but the number of streamers increased. Indeed, there has been significant advances in this throughout the seismic industry in recent years, driven by increased vessel capacity and propulsion. This maintains the geophysical sampling requirements but ultimately has limits based on operational and economic constraints.

Langhammer and Bennion (2015) describe a triple source configuration that increases streamer separation, for example from 100 m to 150 m, whilst switching to three instead of two source arrays. This significantly improves acquisition efficiency whilst maintaining the desired cross-cable sampling. It is compatible with conventional marine acquisition technology, but does require simultaneous or overlapping shooting to maintain fold. This means the data has to go through a deblending process which may impact the signal-to-noise characteristics of the data.

Multimeasurement streamer technology

Robertsson et al. (2008) introduced a new generation of towed streamers that are equipped with hydrophones, to measure the water pressure, and accelerometers, to measure the water particle acceleration in vertical and horizontal directions. From these multimeasurements a dense representation of the upgoing seismic wavefield can be reconstructed at any positions within the seismic spread on a shot-by-shot basis using a process of joint interpolation and 3D deghosting. At the core of the methodology are two main components: noise attenuation based on very fine receiver sampling and single-sensor processing, and a Generalized Matching Pursuit (GMP) as described by Özbek et al. (2010).

This technology has been successfully applied on multiple large-scale exploration projects around the world. Figure 1 shows an example from offshore Mozambique where an accelerated interpretation-ready seismic cube was generated onboard the vessel. The survey was acquired with a standard 12 x 100 m spread.

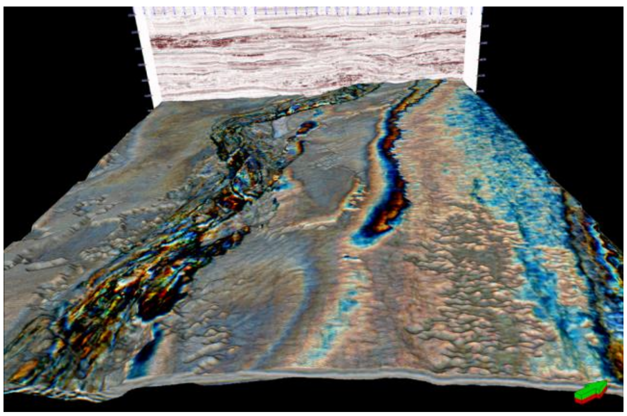

Figure 1: High-resolution definition of Cenozoic channel geometry from a deep water frontier exploration survey acquired using multimeasurement streamer technology with standard 100 m cable separation.

Bayly et al. (2016) showed how a survey acquired using the multimeasurement technology was able to provide a high-resolution image of subsurface despite using a 100 m streamer separation typical of exploration surveys. Results were compared against a dedicated high-resolution multi-beam echo sounder technology used for site survey objectives (Figure 2).

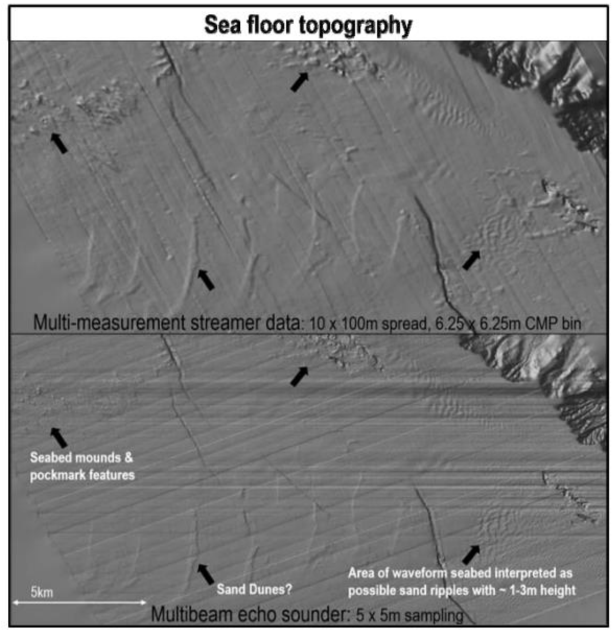

Figure 2: Comparison of multimeasurement streamer technology and multibeam echo sounder data. Similar detailed features at the seabed surface are observed on both datasets. *[From Bayly et al. (2016), images courtesy of IPA]*

These examples demonstrate the potential for multimeasurement streamer technology to deliver high-quality broadband data sets suited for development purposes whilst maintaining a typical exploration configuration.

However, as described earlier, current economic conditions demands greater efficiencies than standard 100 m exploration spreads can support. Here we can leverage a second facet of the multimeasurement acquisition technology. The wavefield reconstruction process is applied in the shot domain and early in the processing workflow. This enables virtual streamers to be reconstructed at any desired location within the spread. For example, virtual streamers may be generated at the midway position between two real streamers – thus halving the cross-cable cmp sample interval. This, in turn, gives the opportunity to relax the tradition survey design restrictions on acquisition geometry. In the next sections we review a selection of geometries designed to improve efficiency without compromising geophysical sampling.

Wide tow streamers and sources

Multimeasurement technology enables streamers to be towed further apart. Wavefield reconstruction generates virtual streamers between real streamers and preserves the desired cross-cable sampling without increasing the number of sources or requiring deblending. The wavefield reconstruction process does include an error, which increases with distance from constraining measurements at real cable locations. Mahat et al. (2014) demonstrated that the reconstruction error is small, but increases with streamer separation (Figure 3). The acceptable degree of reconstruction error depends on the objectives of the survey (e.g. exploration versus development) and should be balanced against the economic benefits of a more efficient approach. In this regard it is no different from the considerations behind other geophysical techniques.

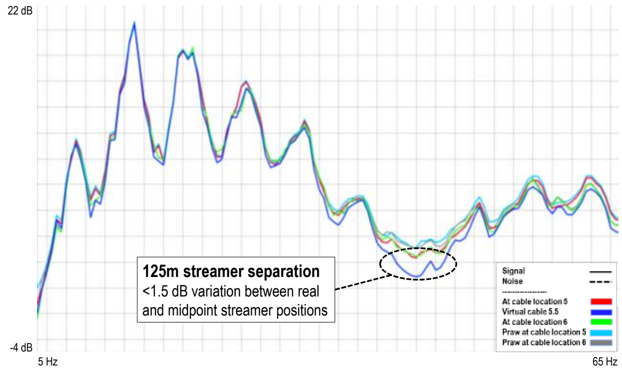

Figure 3: Amplitude spectra comparing wavefield reconstruction results at real streamers (red and green) versus a midway virtual streamer (blue) for a nominal 125 m streamer separation. The curves are generally very close, with only a slight deviation of <1.5 dB observed in the vicinity of the receiver ghost notch frequency. For 75 m streamer separation the deviation is even smaller (<1 dB).

This provides some scope to increase efficiency. For example, expanding streamer separation from 100 m to 125 m and 150 m increases acquisition efficiency by 25% and 50% respectively.

There is also scope to use wavefield reconstruction to allow source separation to be increased. Wide tow sources provide a separate uplift in acquisition efficiency. A combination of these techniques is illustrated in Figure 4.

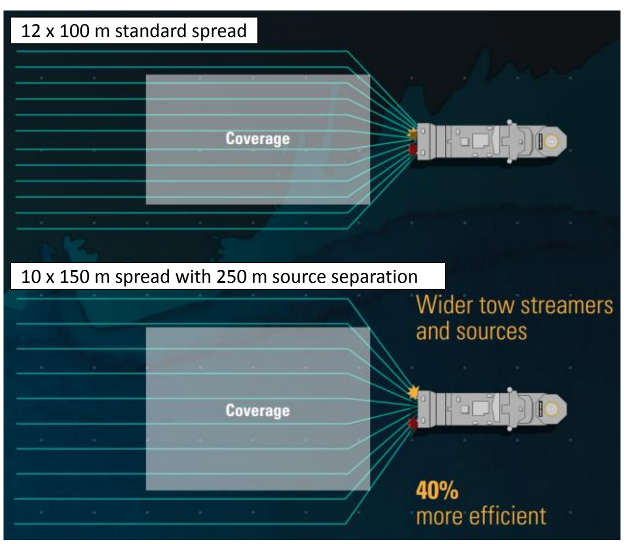

Figure 4: Multimeasurement streamer technology, using wavefield reconstruction, provides a 40% efficiency gain with 20% less streamers in the water.

However, the question remains, is it possible to go further and secure even greater efficiency gains?

Efficient multi-vessel configurations

Various wide and rich azimuth techniques have been extensively used over the last ten years or more, particularly in salt and sub-salt imaging studies. Typical configurations include a 2x4 WAZ which comprises four vessels: two combined streamer/source vessels and two dedicated source vessels. The fleet is arranged approximately line abreast, with an inline stagger to facilitate supershot generation. For spreads consisting of 12 by 100 m streamers, each vessel is spaced approximately 1,200 m from the next. The streamer vessels are positioned on the outer edges of the fleet, with the dedicated source vessels in between. A single source array is used on each vessel. During acquisition, sail lines are interleaved to build the desired offset and azimuth distribution to solve the illumination challenges.

An extension of this technique is to add another source vessel and select relative positions of streamer vessels and source vessels to provide offsets up to 14 km and full azimuth distribution to 6 km, from shooting in one direction, forward and reverse. This is described as a 2x5 WAZ (Figure 5). Other geometries are also possible, however in all cases the aim is to improve imaging rather than increase efficiency.

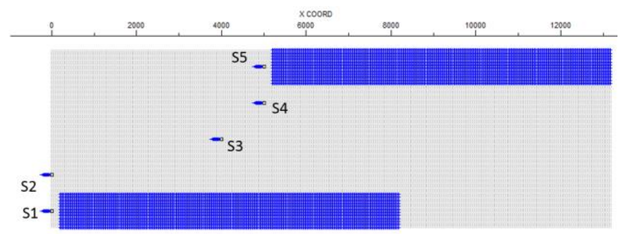

Figure 5: Example of 2x5 WAZ configuration providing both wide azimuth and long offset information. Other configurations are also possible.

Multimeasurement streamer technology can benefit subsalt and pre-salt exploration in several ways, including: (i) to deliver high resolution imaging of shallow sediments and the salt body for velocity model building and migration, which in turn will improve the imaging of the deeper sediments; (ii) dense spatial sampling will minimize the aliasing effects in shot-domain migrations such as RTM; (iii) improved low frequency content from deep, flat tows will be beneficial for subsalt velocity model building and imaging.

The benefit of improved sampling on subsalt imaging is demonstrated in Figure 6. Synthetic data was simulated with 3D finite difference acoustic modelling and RTM imaging using the SEG Seam-1 model for towed streamer acquisition with 10 streamers, 8000 m and 125 m separation versus 50 streamers, 8000 m and 25 m separation (Figure 6a and 6b respectively). The arrows point to the difference in imaging the salt structure (suture and dirty salt) and the reduced aliasing artefacts, due to improved spatial sampling in shot domain of multimeasurement data.

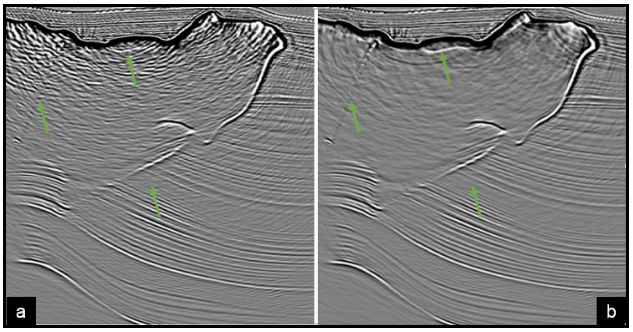

Figure 6: Simulated acquisition for 10 towed streamers with 125 m separation (a) vs. 50 streamers with 25 m separation (b).

In addition, the new multimeasurement streamer supports an acquisition method that could be highly efficient for exploration type surveys in deep water environments Unlike the standard WAZ geometries, the configuration consists of a single streamer vessel and one source vessel, each vessel having a single source array and shooting in flip-flop mode. For this type of configuration the sail line interval can be two times larger than the sail line interval when the data is acquired with a single streamer vessel. For instance, if the streamer vessel is using 12 streamers with 100 m streamer separation, the sail line interval for the acquisition geometry that uses a single streamer vessels is 600 m. If the acquisition geometry consists in a 12 streamer vessel with 100 m streamer separation and a source vessel placed at 1,200 m in the crossline direction (Figure 7), the sail line interval also becomes 1,200 m. This means that the acquisition efficiency can be increased by a factor of two (100%). And extension of this technique involves positioning a third source-only vessel on the opposite side, providing a further increase in efficiency (200% compared to the single vessel baseline).

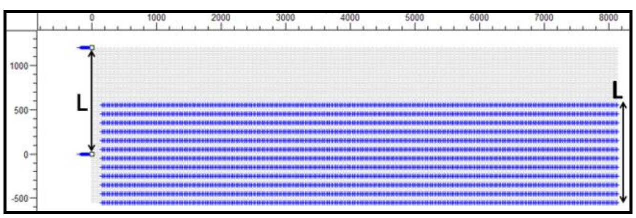

Figure 7: A multimeasurement streamer vessel and a source vessel; the separation between the streamer vessel and the source vessel is equal to the streamer spread width (L); the sail line interval for this configuration could be equal to the spread width (L)

This type of acquisition geometry is feasible for water depths larger than 700 m. This will allow to acquire non-critical water bottom reflections and reconstruction of surface related multiples will be possible from recorded multiples. AVO type processing is feasible with this geometry but, depending of the water depth, and velocity contrast at the water bottom, small angles of incidence could not be recorded. We conducted a modeling study of this type of acquisition to compare a narrow azimuth survey acquired with a single streamer vessel towing 12 streamers, 8,000 m length, 100 m separation and a dual vessel survey using a multimeasurement streamer with the same streamer configuration (12 x 8,000 m x 100 m) and an additional source vessel, as presented in Figure 7. The sail line interval was 600 m for single streamer survey and 1,200 m for the dual vessel survey. The data was simulated with 3D wave equation acoustic finite difference modeling with 20 Hz maximum frequency and including free surface related multiples. The water depth for this simulation was more than 1,000 m. For the multimeasurement streamers we assumed that the data was reconstructed on a receiver grid that had 24 streamers x 8,000 m x 50 m separation. In Figure 8a, we show a vertical section in the inline direction from the SEG SEAM model used for seismic simulation and in Figure 8b and 8c we show, respectively, the RTM migrated images corresponding to the single vessel streamer acquisition and to the dual vessel acquisition. These results show that migrated image corresponding to the dual vessel configuration using 1,200 m sail line interval is similar or better than the results of single streamer acquisition using 600 m sail line interval.

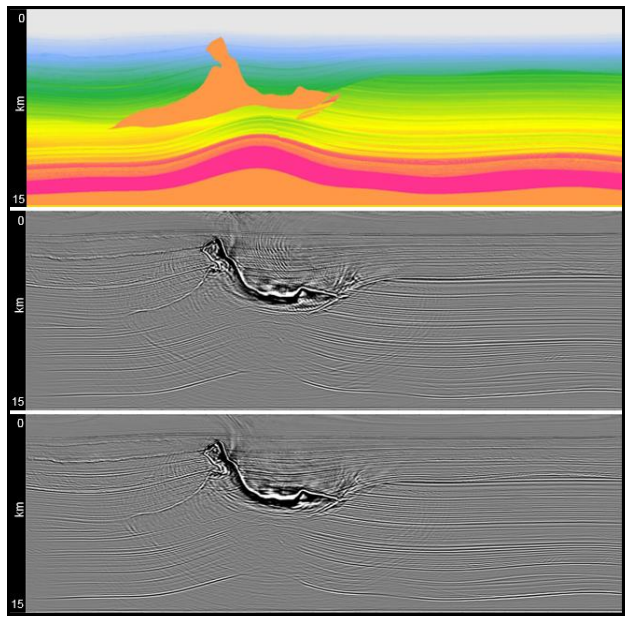

Figure 8: The SEG Seam model used for 3D finite difference simulation (top); RTM migrated image for single vessel acquisition with 600m sail line interval (middle) and RTM migrated image for dual vessel configuration with a multimeasurement streamer, one source vessel and 1200 m sail line interval (bottom).

Multimeasurement wavefield reconstruction for wide azimuth geometries

It has been shown that multimeasurement streamer technology can benefit sub-salt imaging and also improve acquisition efficiency. These methods rely on the ability to reconstruct the seismic wavefield between streamers. A field test was carried out offshore Mozambique to validate this approach. Two streamer vessels were positioned 3,600 m apart to replicate the positioning of a standard 2x4 WAZ survey. Both were equipped with multimeasurement streamers.

Sources from one vessel were recorded into the opposing vessel (thereby acquiring WAZ data) as well as into its own spread (providing a NAZ baseline for comparison). Figure 9 shows good signal-to-noise characteristics on all three multimeasurement data sets prior to input to the wavefield reconstruction process. In particular, the cross-cable Y measurement shows strong signal content in the WAZ geometry compared to the NAZ equivalent. This is in line with expectations and demonstrates that crossline propagating energy can be a significant component of the seismic wavefield, even in deep water environments.

Results of the wavefield reconstruction process show that the multimeasurement wavefield reconstruction process performs well for WAZ-style geometries. In more complex geological environments, such as salt provinces offshore Brazil, then wavefield propagation will be even more complicated – resulting in greater energy recorded on the Y measurement. This also applies for full azimuth acquisition geometries such as coil and dual coil shooting

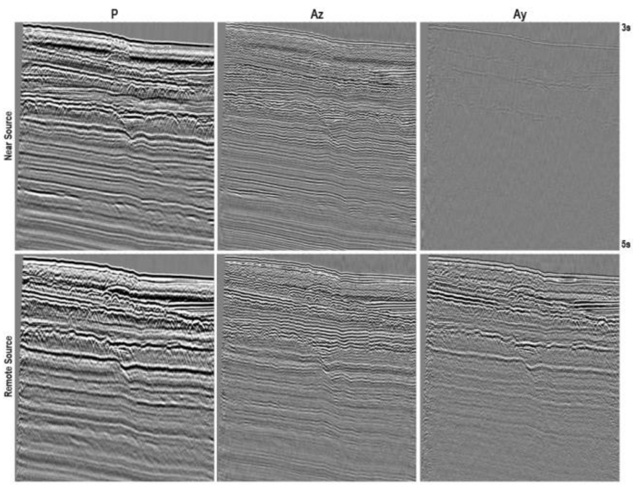

Figure 9: Stack sections comparing measurement quality for near (NAZ) and remote (WAZ) sources. Note the strong signal content on the Y measurement for the WAZ configuration.

Conclusions

Successful sub-salt exploration requires seismic data with good broadband characteristics, plus rich azimuths and offsets. Economic pressures also place a renewed emphasis on cost effective exploration. In this paper, we described a new multimeasurement towed-streamer acquisition technology which could be beneficial for subsalt and pre-salt reservoir exploration.

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