Full azimuth towed streamer seismic; a pre-salt exploration tool

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Abstract

With a string of recent discoveries in the pre-salt areas in deep-water offshore Brazil, this hydrocarbon province has already been proven to be of global importance. The pre-salt reservoirs, however, present many challenges for exploration. In this paper we describe the acquisition and processing of a full-azimuth towed-streamer seismic survey designed for pre-salt exploration offshore Brazil. We show that this solution overcomes many of the pre salt exploration challenges to provide high quality reservoir information in an efficient manner.

Introduction

This project relates to the imaging of a pre-salt aptian carbonate reservoir located in Santos basin, BM-11 block in ultra-deep water, which was discovered on August 2008. This pre-salt reservoir is estimated to hold 3 to 4 billion barrels of light oil and natural gas at a depth of approximately 6000m, varying in thickness from tens to hundred's of meters. This study was carried out to improve the structural information of the reservoir but also to characterize the reservoir properties including the reservoir fracturing.

The reservoirs are structurally bounded by tectonic faults associated with the separation of the South Atlantic. The overburden consists of a complex dipping salt-layer up to two thousand meters thick, consisting of both homogeneous halite bodies and layered evaporates. The salt is in turn overlain by Albian carbonates and inter-bedded sands and shales. The complex propagation of the seismic wavefield within this geological environment provides a challenge not just to acquire data which adequately illuminates the reservoir events at depth, but also to process the data such that the data is free from noise and is represented in its true geological context.

This paper will focus on the challenges and resolutions of the data processing phase of this project, and just provide a summary of the acquisition and survey design phases which have been addressed by previously published papers.

Survey Design, Planning and Acquisition

The survey design, planning and acquisition phases of this project have been previously covered by Le Diagon et al (SBGF 2011). In areas of geological complexity, such as this project, a conventional towed streamer acquisition measurement can result in inconsistent and poor illumination, and consequently imaging, of the target reservoirs because the seismic wavefronts bend and scatter as they propagate through the complex overburden. Coil is one of a number of proven solutions to mitigate for this limitation of the towed marine method by using more sophisticated surface geometries (Kapoor 2007). With some exceptions the use of these more sophisticated geometries has been quite limited offshore Brazil. Coil (Moldoveanu et al 2008) is a technique in which a 3D marine towed streamer geometry follows a circular pre-plot which is repeated spatially to build up fold, offset and azimuth distribution. Figure 1 details the pre-plot offset azimuth distribution averaged over a 5km^2 zone in the central portion of the proposed acquisition area.

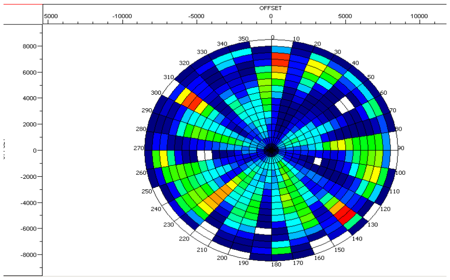

Figure 1 – Pre-plot offset and azimuth distribution averaged over the central (360^o azimuth zone) of the proposed Iara acquisition area.

After an intensive survey design and modeling effort to assess and demonstrate the value of a full azimuth acquisition measurement, Petrobras decided to move forward with a coil shooting solution. The survey was acquired between November 2010 and January 2011 over an area of approximately 625 km^2.

Streamers	*12x8000m*
Source	*2x5085 in^3*
Shotpoint Interval	*37.5m*
Streamer Depth	*12m*
Source Depth	*10m*
Streamer Separation	*120m*
Source Separation	*60m*

Table 1 – Key acquisition parameters

The key acquisition parameters for the project are detailed in table 1 and the source locations and fold of coverage plot are available in figure 2.

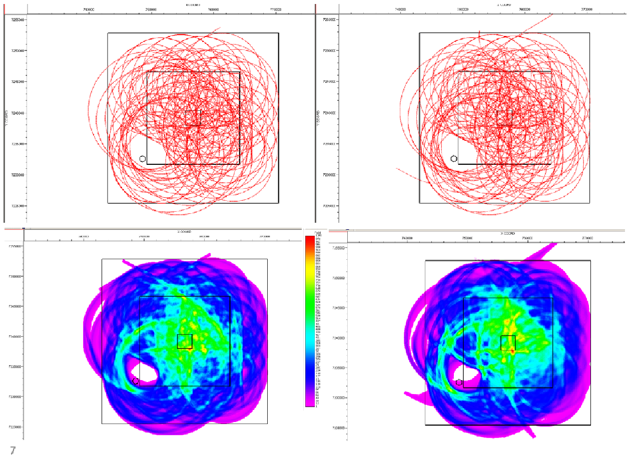

Figure 2 – Survey source locations and fold of coverage maps. Pre-plot figures on the left and post-plot figures on the right with source location maps on the top and Fold of coverage maps on the bottom.

Data Processing

While the coil measurement is theoretically better sampled, there are aspects of the acquisition technique and geometry which add complexity to the data processing effort (Buia et al, 2010).

- The process of following a circular "line" results in increased cable curvature which consequently increases the cross-flow noise as this curved streamer is dragged through the water column.
- While the coil acquisition is very well sampled, with fold of coverage greater than 1000 in the central portion, the sampling is relatively irregular. Straight line towed streamer measurements while of very limited azimuth aperture are regularly sampled in offset and can use data processing algorithms which assume regular geometry without negatively impacting data quality. Successful coil data processing needs to consider the measured source and receiver co-ordinates.

Noise Attenuation: To address the higher levels of noise resulting from the higher streamer curvature a very intensive point receiver processing flow was developed. As with all coil surveys the project utilized a Q-Marine vessel which makes a point receiver measurement every 3.125m along the streamer. Rather than using the realtime noise attenuation workflow, the onboard processing team returned to the point receiver data and applied a more intensive flow prior to re-sampling to 6.25m trace interval. The cross-flow noise modes while low frequency are also very low velocity (less than 100m/s) and will be heavily aliased at the more normal trace intervals of 12.5m. After much testing and refinement the final point receiver workflow (figure 3), comprised of four noise attenuation approaches including Single Value Decomposition (SVD) which was specifically designed for coil acquisition by Moldoveanu (2011). Figure 4 details the point receiver data before and after application of this workflow, showing the effectiveness of the workflow to address the very high amplitude noise bursts, without cutting into the signal cone. This workflow was applied in near realtime on the vessel and additionally includes two applications to address signal perturbations (Offset regularization and receiver motion compensation).

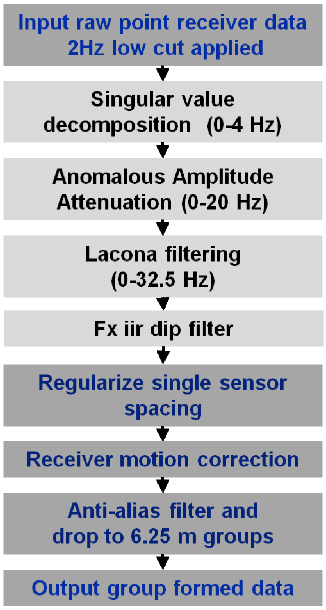

Figure 3 – Near realtime point receiver processing flow designed to address the high level noise bursts while preserving the signal.

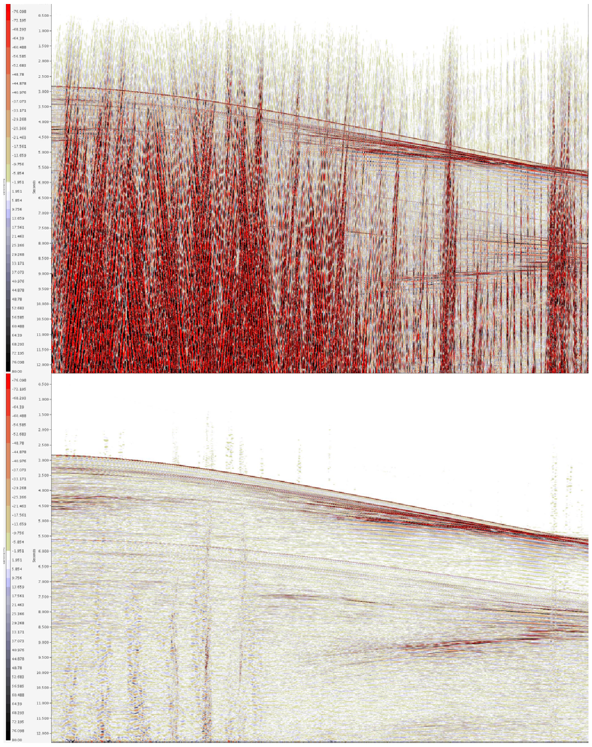

Figure 4 – Raw point receiver data (top) showing high levels of noise and after infield digital group forming (bottom).

Water-velocity Correction: It is well known that variations in the velocity of sea water during the acquisition of

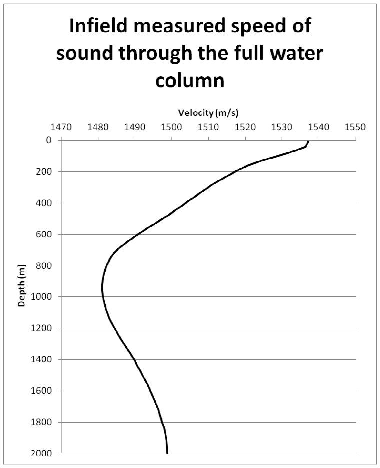

Figure 5 – Graph displaying the infield measurement of the velocity depth profile. Note this follow the general shape of other library profiles with a reduction in velocity to 1000m depth followed by an increase in velocity at further depth.

marine seismic surveys leads to differences in the travel time of the same reflection events acquired by different sail-lines. This leads to errors in all aspects of the data processing flow from velocity analysis to stacking, in instances where midpoints contain traces from multiple sailines which may have been acquired with a large time lag. The rapidly changing current regimes characteristic of offshore Brazil ensure that such variations in water-velocity are of a significant magnitude, and vary rapidly. This problem becomes even more critical to solve for coil data, where many different coils (each with its own water-column velocity profile) contribute data to each midpoint; Even with efficient well planned coil acquisition the time duration to build up the fold of a single midpoint can be of the order of weeks. Conversely, with straight line surveys the time difference between adjacent lines, which contribute to the same mid-point, is generally quite short.

It is also well know that the water column velocity changes with depth due to changes in water temperature and salinity content. This depth dependent water column velocity profile cannot be estimated from the seismic reflection measurement, but if not accounted for will impact the depth imaging effort; Any errors in the water column model will propagate deeper into the model during reflection tomography.

For this project, we used the approach of Carvill (2009) to account for the spatial variance and to correct to a depth dependent water column velocity profile which in this case was measured in the field using a temperature-salinity probe (Figure 5). Simplistically the Carvill approach compares the reference velocity profile with the water bottom RMS velocity and water depth to compute and apply a static shift to the seismic data on a shot-by-shot basis. Figure 6 details the application of water velocity correction and the successful removal of the water bottom reflection jitter.

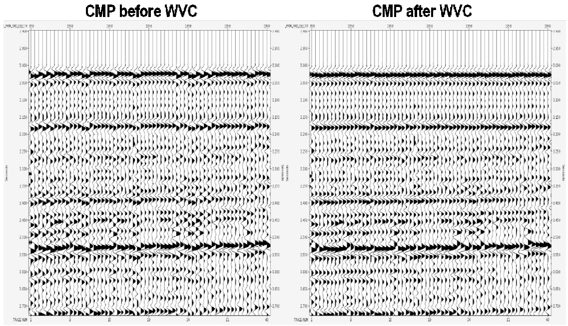

Figure 6 – CMP before (left) and after(right) water velocity correction.

Multiple Attenuation: In this deep-water environment, the first-order surface-multiple from both the sea-floor and complex top of salt reflector coincide with the weaker base of salt and pre-salt reflections. It was, therefore, critical to attenuate this energy without corrupting the primary amplitudes beneath. This effort is further complicated by the diffracted multiples, primarily generated at the complex top-salt and rugose waterbottom. Data driven techniques such as True azimuth 3D SRME (Dragoset et al 2008) have proved successful at addressing similarly complex multiples but are known to benefit from dense shot and receiver sampling and short near offsets. The coil design, by its nature, provides high density shot sampling and a more diverse sampling of near offsets. Figure 7 details the application of 3D SRME. For this project true azimuth 3D SRME was applied as part of multiple attenuation workflow.

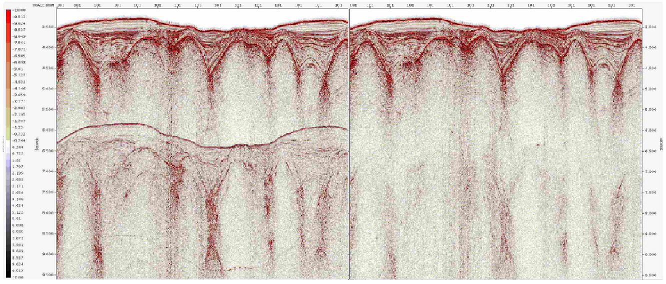

Figure 7 – Single near offset gather pre 3DSRME (left) and post SRME (right)

Regularization: Coil geometries are very high fold when compared to both wide-azimuth and narrow azimuth straight line surveys. However the data coverage in terms of offset, azimuth and midpoint is inherently irregular over the area of a coil survey, with the azimuth and offset distribution varying spatially; most significantly in the taper zones. While this is not necessarily a concern for shot based imaging algorithms, for some data processing algorithms, such as tomographic velocity-model building, it is desirable to have coverage within CMPs which is regular in terms of midpoint, azimuth and offset.

There are several different methods to achieve this, and different methods were used as appropriate for different parts of the data-processing sequence. To build the velocity model in the sediments, Compact Fourier Interpolation (Moore et al 2008), recently extended to efficiently interpolate in multiple dimensions, was used to produce fully-regularized data in offset, midpoint and azimuth. Figure 8 details a inline from a common offset/ common azimuth gather before and after multi dimensional COMFI.

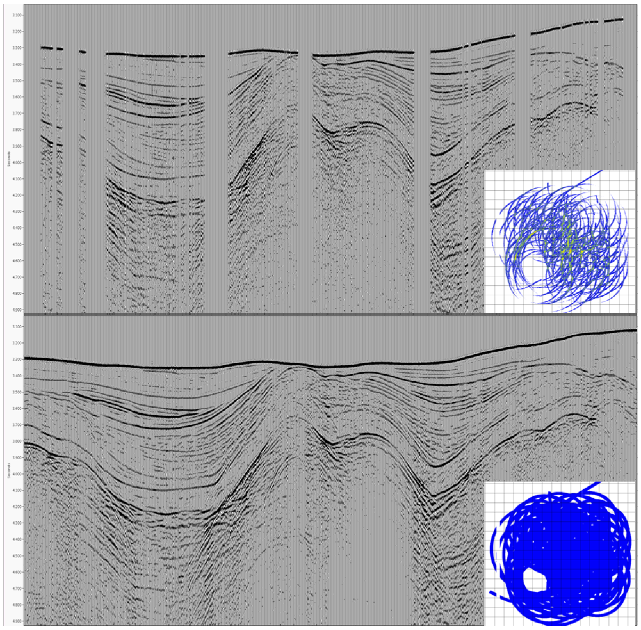

Figure 8 – An inline from a common offset /azimuth volume before regularization (top) and after regularization (bottom) with fold of coverage distribution inset.

Hole Filling: The acquisition was restricted by a platform in the south west quarter of the survey area. The acquisition was designed to shoot around the obstruction whilst ensuring full azimuth coverage in the center area. The hole remaining around the obstruction was filled with legacy narrow azimuth data.

Petrobras provided pre-stack data to cover the hole plus an additional 6km migration aperture. Pre-processing of the legacy data followed a very similar approach to the full azimuth measurement but included the wavelet matching step in which differences in the source and receiver response of the two datasets were compensated for. The MAZ tomography segments were specifically chosen with the legacy data in mind. The legacy survey was shot at a 90 degrees azimuth and it was merged to the 45 to 135 degree azimuth band. For final migration s (RTM and KPSDM) both surveys were merged and migrated together.

Imaging: In complex areas such as these, the development of an accurate velocity model for depth imaging is essential to correctly represent reflections in their true geological positions. With full-azimuth acquisition, multi-azimuth tomographic methods can be used for velocity-model updating. Dazley et al (2007) showed how the introduction of additional information from multiple azimuths in reflection tomography reduces uncertainty and gives more confidence in more detailed velocity-model updates. In our case, the data was split into three azimuth volumes for multi-azimuth tomography (0-60, 60-120 and 120-180, and their reciprocal azimuths). Anisotropic (TTI) Kirchhoff depth migration was used to update the velocity model, which was performed in three layers; sediment, intra-salt and presalt. The anisotropy model was based on a regional trend provided by Petrobras.

Validation of the earth model included 3D VSP traveltime analysis, where measured and modeled 3DVSP arrival times are compared to produce a measure of confidence in the model. Figure 9 shows a map of the travel time residuals after completion of the fourth and sixth run of sediment tomography. This is a very limited example of what can be achieved by integrating surface seismic and borehole data. With more time the borehole data could have been used to calibrate the anisotropy model and potentially used in a joint velocity inversion.

The final migration image was produced using anisotropic Reverse Time Migration (RTM).

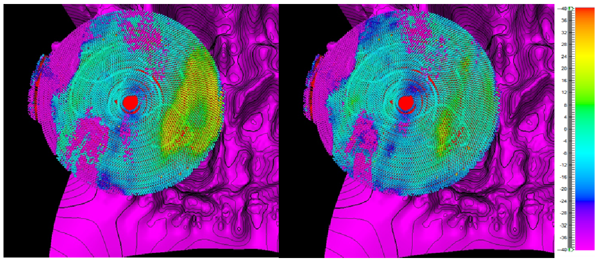

Figure 9 – 3DVSP residual travel time QC; using earth model after tomography update 4 (left) and after tomography update 6 (right). The reduction of the direct arrival travel time difference (measured – ray-traced) further validates the velocitv refinement.

Results

Figure 10 shows a line from the existing 2D depth-migrated multiclient data in the area (left) compared with a depth migration of the coil data, using an intermediate 'salt flood' velocity model. It can clearly be seen that the 3D provides a step-change in imaging improvement over the 2D data, and that the pre-salt reflections are well imaged.

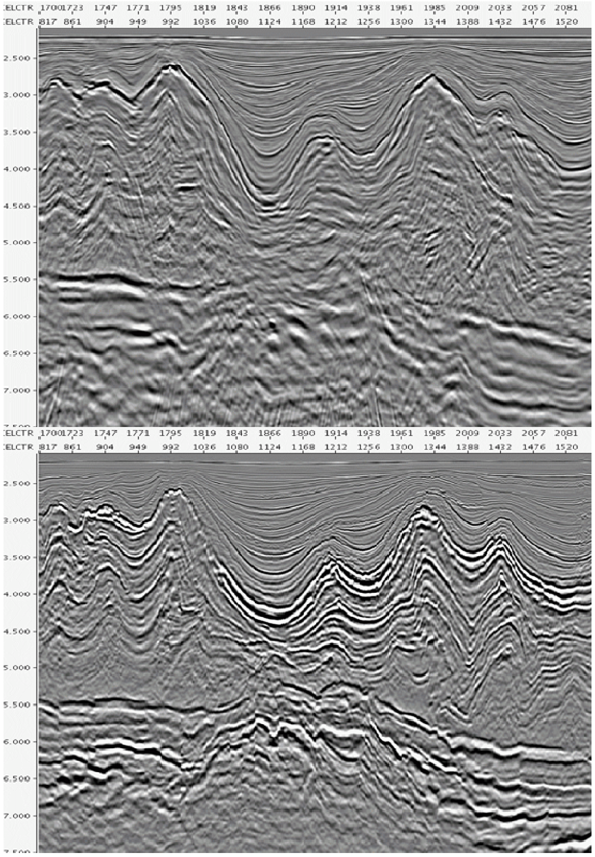

Figure 10 : Co-located existing 2D migration (top) and Kirchhoff depth migration of the coil dataset (bottom). Note the improvement in reflectivity and resolution of the pre-salt sequence between 5.5 and 7km depth.

Conclusions

Coil acquisition is an efficient tool for acquiring full azimuth towed-streamer seismic data offshore Brazil, and a data-processing sequence has been developed for the coil data in deep-water Santos basin which both overcomes the challenges and exploits the benefits associated with the technique to provide high quality information for pre-salt hydrocarbon exploration.

Acknowledgments

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