Full-azimuth towed-streamer acquisition and broadband processing in an obstructed area of the Gulf of Mexico

Carlos Espinoza, Olga Zdraveva, Barbara Curd, Eugene Gridnev and Nick Moldoveanu, WesternGeco

Abstract

South Timbalier is a relatively mature and highly obstructed field located in the Gulf of Mexico. The oil production is mostly from shallow, post-salt reservoirs, analogous to those found in Brazil's Campos and Santos Basins. These shallow reservoirs were originally discovered with old seismic acquisition, data processing and imaging technology and require enhanced definition with new technology to maximize recovery. To achieve that and to help unveil the potential deeper subsalt plays, a full-azimuth (FAZ) towed-streamer survey was acquired in 2014. FAZ acquisition geometry was specifically chosen to address illumination challenges similar to those in Brazil's presalt areas.

In this paper we discuss the solutions used in seismic acquisition, data processing, velocity model building, and imaging in general, to deliver a high-definition subsurface image allowing reliable interpretation of both: known presalt and potential new subsalt targets.

Introduction

This FAZ towed-streamer seismic survey was acquired in 2014 over 118 Outer Continental Shelf blocks (2920 km²) in the South Timbalier area of the Gulf of Mexico. The objectives were to allow more accurate mapping of shallow reservoirs, to improve seismic illumination and the interpretation of salt flanks, subsalt, and salt-associated plays, and to help better identify direct hydrocarbon indicators (DHI-s). Similar to the post-salt turbidite-bearing section offshore Brazil in the Campos and Santos Basins, the previously discovered reservoirs are mainly at shallow, normally pressured, depths below the sea floor in basin floor fan, channelized fan, and rafted fan environments. Typical traps have a strong stratigraphic component but many are also fault modified. DHI detection, based on amplitude analysis and seismic inversion, is commonly used to map prospective reservoirs and mitigate geologic risk.

The deeper section, including the subsalt environments, is relatively unexplored, with very few wells drilled below 4500 m. The new FAZ acquisition and imaging also helps resolve vertical sediment salt interfaces as well as providing better guidance to the drilling effort to access potential up-dip portions of the strata terminating against the salt face.

The South Timbarlier FAZ survey is located in an area highly obstructed by drilling infrastructure (Figure 1). Several older vintages of seismic data, shot with narrow-azimuth (NAZ) towed-streamer and ocean bottom cables (OBC) acquisition, exist in this area. A survey design and modeling study was performed to determine if an alternative acquisition solution to ocean-bottom systems was feasible using towed-streamer acquisition and the existent seismic data, to complement the new data.

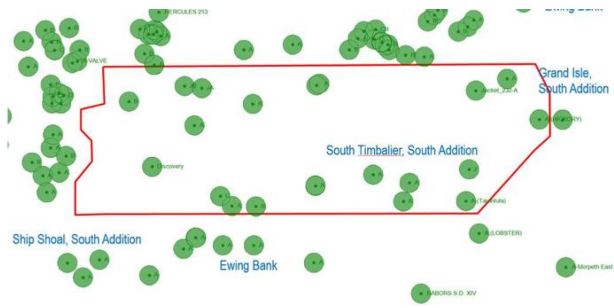


Figure 1 – *Situation map: South Timbalier FAZ survey outline is marked in red and the existent platforms and rigs are marked in green.*

Acquisition solution

The proposed acquisition solution, based on the survey design and modeling study, was to use coil-type geometry (Moldoveanu *et. al*., 2008) with one streamer vessel, towing relatively short streamers, and an additional source vessel, 5 km behind the streamer vessel (Figure 2), to acquire full-azimuth data with 10,000-m maximum offsets. The two vessels sailed on two different circles, with 5500-m radii. The streamer configuration consisted of 10 streamers, 5000 m in length and with 120 m of separation. Towing these relatively short streamers allowed the vessels to safely navigate around platforms. A single source array with a volume of 8475 in³ was deployed on each vessel; the shot interval was in time mode, equivalent to approximately 31.25 m, flip-flop, shooting. The depths of the source arrays and streamers were 10 m and 12 m, respectively.

A 3D ray-tracing illumination study was performed that combined the proposed circular acquisition geometry and the existing seismic data. This showed that the holes in the subsurface coverage due to the obstructions could be filled. In Figure 3a, we show an illumination map for a 0- to 2000-m offset range using the proposed circular acquisition geometry. The holes in the illumination map are filled if NAZ data are used together with circular acquisition data (Figure 3b).

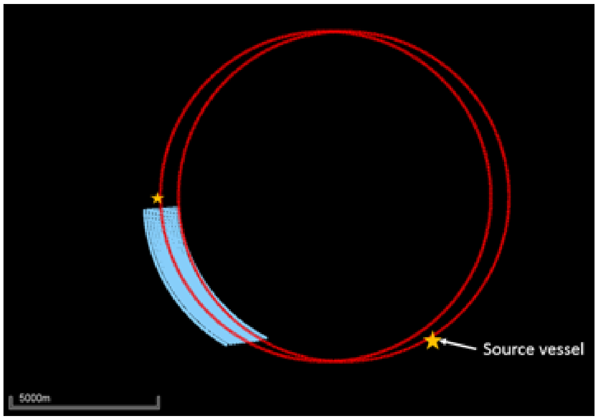
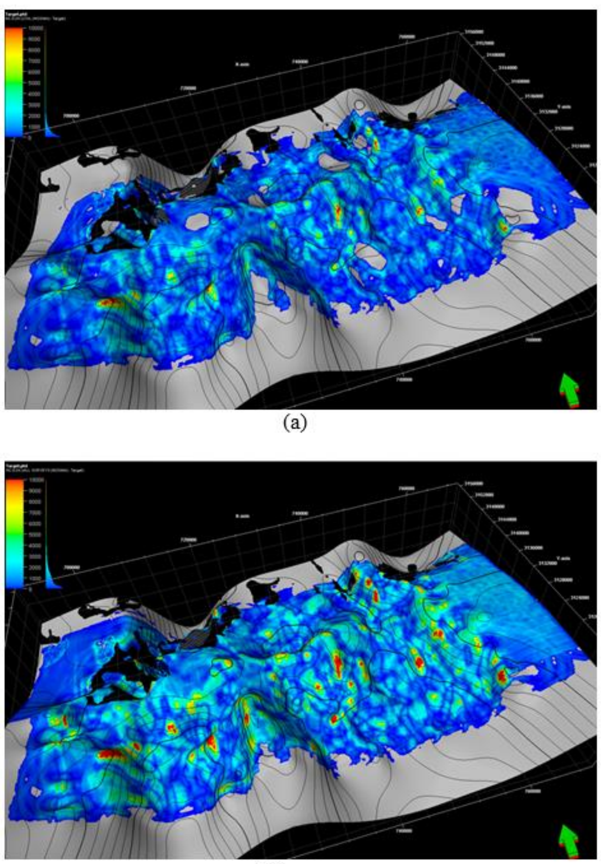


Figure 2 *- Circular shooting with one streamer vessel and a source vessel 5 km behind; the circle radius was 5.5 km*



(a)

(b)

Figure 3 *- Illumination map for 0- to 2000-m offset range: (a) using proposed circular acquisition; (b) using combined, circular acquisition and existent NAZ data.*

To have a short acquisition turnaround time, it was decided to use two identical seismic crews. The survey shape allowed us to operate these two crews with a minimum 25-km separation distance to minimize seismic interference. The survey was acquired in 72 days.

Processing aspects

One of the challenges in data processing was to increase the bandwidth of the seismic data. The strategy to achieve this was based on the following processing steps:

1) A multistep noise attenuation flow to minimize any residual noise, particularly at very low frequencies;
2) Pre-migration application of receiver deghosting, source deghosting, and inverse-Q (phase only);
3) Post-Migration application of depth-variant inverse-Q (amplitude only) and bandwidth extension.

The deghosting method employed was an inversion-type algorithm that solves for the upgoing wavefield or deghosted pressure data (Webb*, et. al.*, 2013). It requires fine receiver sampling and knowledge of source and receiver depths, water velocity, and sea-surface reflection coefficient. By design, data acquired with circular shooting has a crossline component. However, ghost modeling with a 2D assumption still produced a good solution with rapid turnaround. An example is shown in Figure 4.

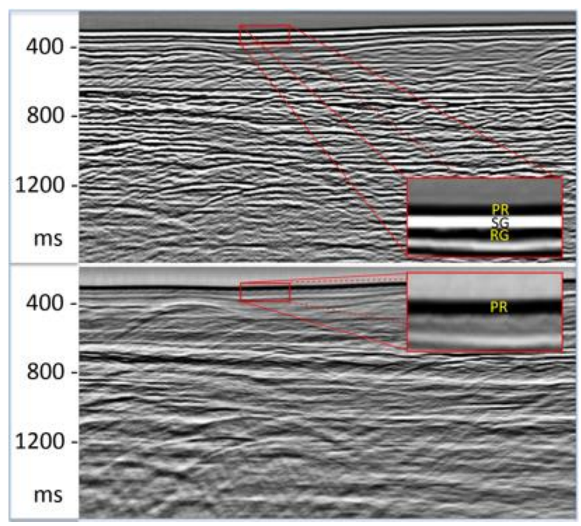


Figure 4 *- Stack before (top) and after (bottom) deghosting*

Attenuating sea-surface-related multiples was another challenge. It required reprocessing all the existent NAZ data to improve data population, particularly near offsets, and using it together with the new data for prediction and adaptive subtraction of the multiples. A 3D surface-related multiple elimination (SRME) algorithm that can handle any type of acquisition geometry was used for the prediction step (Dragoset *et. al*., 2010). This was followed by a L1-norm cascaded adaptive subtraction workflow. An example of prestack Kirchhoff depth migration (KDM) image, before and after surface multiple attenuation, is shown in Figure 5, illustrating the effectiveness of the demultiple process. This migration used a preliminary velocity model.

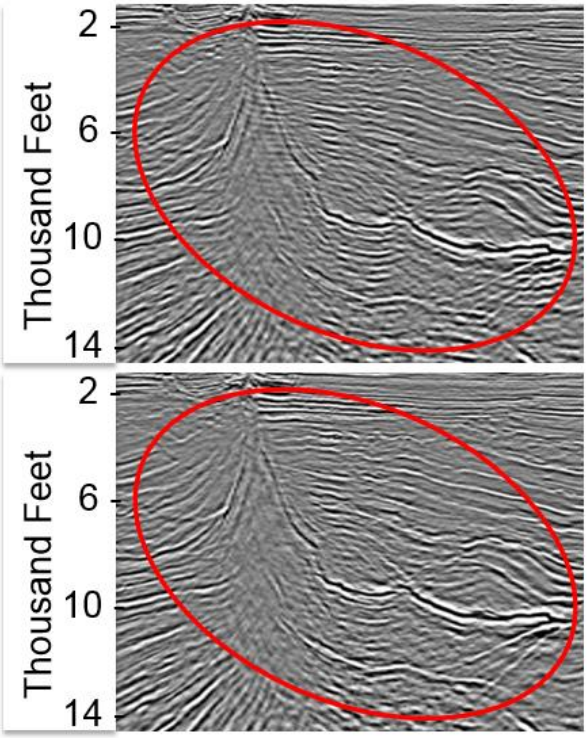


Figure 5 – *KDM image before (top) and after (bottom) surface-related multiple attenuation.*

Velocity model building

Accurate imaging and positioning small faults and the stratigraphic traps in the shallow sediments, the deeper salt bodies, and subsalt structures require a good-quality anisotropic velocity model. We built a high-resolution tilted transversely isotropic (TTI) model by following closely all the steps outlined by Zdraveva *et al.* (2011), with an additional full-waveform inversion (FWI) step introduced after first iteration of common image point (CIP) tomography (Woodward *et al*., 2008).

The role of FWI was to complement tomography in the shallow section, where picking moveout might be cumbersome due to limited number of traces and prevalent stretch energy.

The key challenge for FWI was addressing shot and receiver density differences between legacy NAZ and circular acquisition data. Limiting the data to diving waves and using a new FWI algorithm designed to mitigate cycle-skipping issues related to inaccuracies in the background model (Jiao *et. al*., 2015) produced robust results.

Five iterations of multiazimuth, multiscale TTI tomography (Woodward *et al.,* 2008) with implicit geologic constraints (Zdraveva *et al.,* 2013) produced the significant uplift in quality and resolution of the post-salt section. The final velocity model is very detailed, including fault delineation and stratigraphic layers (Figure 6).

The subsalt velocity model building workflow involved a combination of rock-physics-constrained initial model building, calibration with existing well information, and two additional iterations of through-salt and subsalt CIP tomography with implicit geologic constraints.

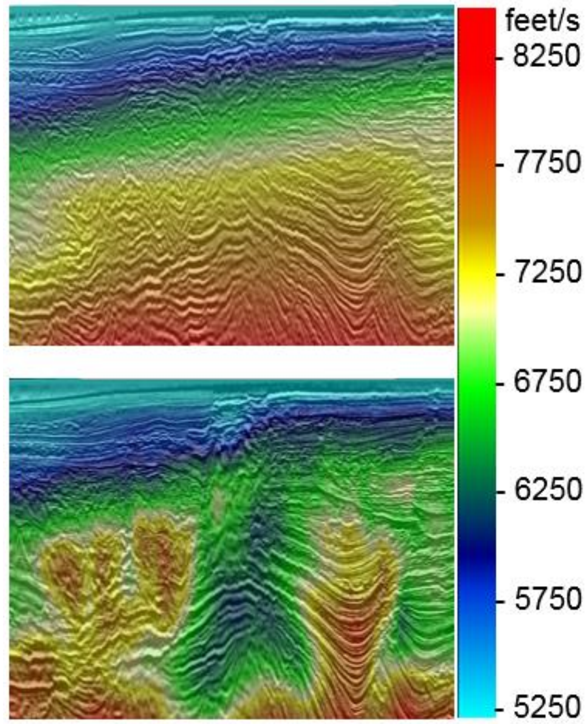


Figure 6 – *KDM image before (top) and after five iterations of tomography; velocity color scale is on the right side*.

Results

Both data sets, the existent NAZ data and the new circular acquisition FAZ data, were migrated with KDM to a 90-Hz maximum frequency, and with reverse time migration (RTM) to a 35-Hz maximum frequency. The output bin size for KDM was 12.5 m (inline) x 15 m (crossline) x 3.04 m (depth) and for RTM migration it was 25 m (inline) x 30 m (crossline) x 9.75 m (depth). For both migrations the aperture was set to 9000 m.

Optimal stacking of NAZ and FAZ images for interpretation of deeper targets used vector image partitions (Zhao *et. al.*, 2015) generated during RTM. An example of a simple sum of the NAZ and FAZ RTM images is shown in Figure 7. The azimuth diversity and long offsets, provided by the new FAZ survey, effectively illuminated subsalt targets and produced high-quality images for salt geometry interpretation and prospective geologic play identification.

High-resolution KDM with fine sampling and large aperture imaged the heavily faulted shallow section very well. Figure 8 highlights the faults and fractures visible in a shallow depth slice after the edge detection attribute was calculated.

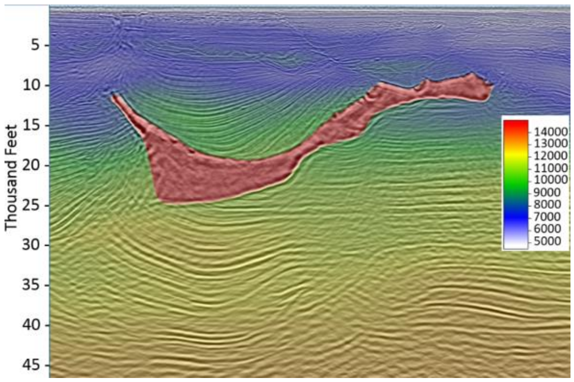


***Figure 7 -** RTM image of combined NAZ and circular acquisition data*

***Figure 8 -** Depth slice through the edge detection attribute showing clearly many fractures and faults affecting the post-salt sediments*

The impact of enhanced imaging also extends to the derivation of many other seismic attributes, enabling more accurate geological mapping and interpretation and reducing drilling exploration risks through better understanding of shallow hazards. Figure 9 shows a transform into continuous color domain, where seismic data is processed in a way similar to the processing of satellite imagery.

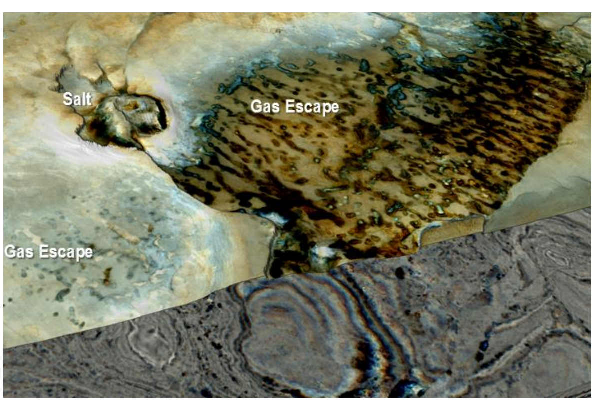


***Figure 9 -** RGB attribute highlighting potential geohazards*.

The combination of high-resolution tomography and broadband processing reveals narrow-scale features such as channels and stratigraphic reservoirs. An example of a known post-salt, shallow reservoir, imaged with KDM, is shown in Figure 10, illustrating that the relative amplitudes were properly preserved during data processing and imaging. KDM gathers have several instances of AVO anomalies visible at large offsets. A careful spatially variant mute was required to preserve the far-offset signal.

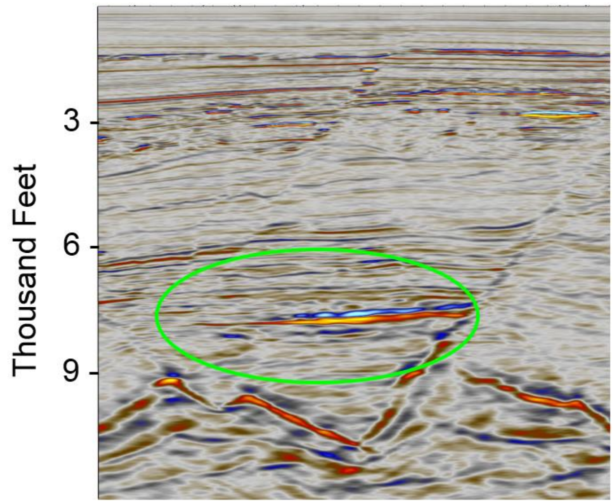


***Figure 10 -** Example of a post salt reservoir after high resolution KDM*

Finally, Figure 11 shows poststack inversion results of the new volume combining legacy NAZ and new acquisition FAZ versus NAZ only, with the same velocity. The higher quality of the acoustic impedance in the new volume demonstrates the leverage of the combination of FAZ acquisition, broadband processing, and high-resolution model building and imaging to obtain potential direct hydrocarbon indicators.

Conclusions

The subsurface imaging results from this survey show very good definition of post-salt and subsalt sediments. This allows accurate mapping of the stratigraphic and fault traps, delineation of the salt bodies, subsalt structure or salt associated reservoirs, and amplitude anomalies potentially related to fluid presence.

Towed-streamer circular acquisition using one receiver vessel, towing relatively short streamers, and a source vessel placed behind the streamer vessel, proved to be an efficient method to acquire full-azimuth and a 10000-m maximum offset in a highly obstructed area on the Gulf of Mexico Shelf. Reprocessing all underlying NAZ seismic data was essential to complement the new data.

Broadband processing improved the low-frequency content of the data and yielded increased seismic resolution, continuity of the subsalt events, and phase fidelity for velocity model building and inversion.

High-resolution multiscale multiazimuth CIP tomography provided the greatest impact on imaging results, enhancing post-salt definition, including existing stratigraphic and fault traps reservoirs, and enabling salt delineation and identification of potential new subsalt plays.

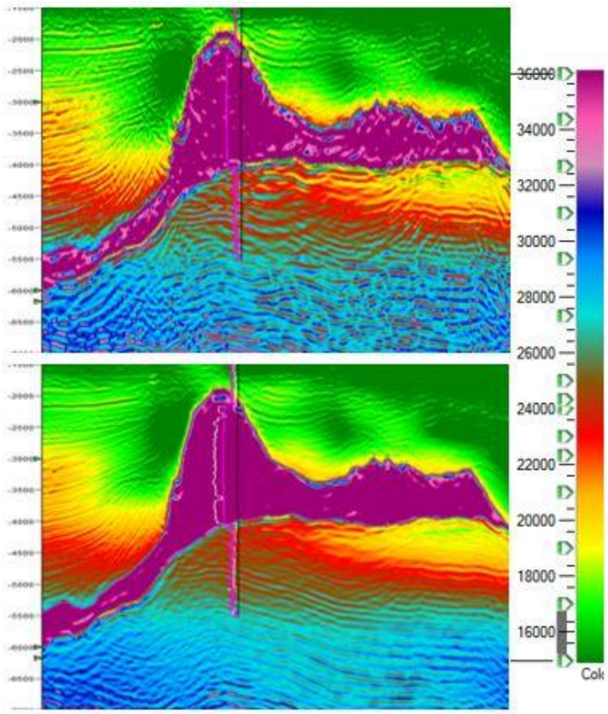


Figure 11 - *Inversion with legacy NAZ (top) and new volume (bottom). Both with the same final velocity field.*

From an economic point of view, the acquisition solution we used for this project is very attractive for other highly obstructed areas, where OBC or ocean-bottom nodes acquisition geometries are typically required.

Acknowledgements

We thank WesternGeco for permission to use multiclient data and present these results, and we acknowledge the contributions of Alexander Zarkhidze, Saeeda Hydal, Clive Gerrard, Seet Li Yong, Zach Wolfe, Myla Kilchrist, and the South Timbalier data processing team.

References

DRAGOSET, B.; VERSCHUUR, E.; MOORE, I. and BISLEY, C. 2010. A perspective on 3D surface-related multiple elimination: GEOPHYSICS, **75**(5), 75A245-75A261, doi: 10.1190/1.3475413.

JIAO, K.; SUN, D.; CHENG, X. and VIGH, D. 2015. Adjustive full waveform inversion: 85th Annual International Meeting, SEG, Expanded Abstracts, 1091-1095.

MOLDOVEANU, N.; KAPOOR, J. and EGAN, M. 2008. A single-vessel method for wide-azimuth towed-streamer acquisition. 78th Annual Meeting, SEG, Expanded Abstracts, 65-69.

WEBB, B.: HILL, D. and BRACKEN, S. 2012. Slanted–Streamer Acquisition – Broadband Case Studies in Europe / Africa. 75th EAGE Conference and Exhibition, Extended Abstracts.

WOODWARD, M.; NICHOLS, D.; ZDRAVEVA, O.; WHITFIELD, P. and JOHNS, T. 2008. A decade of Tomography. Geophysics, **73**, 5-11.

ZDRAVEVA, O.; WOODWARD, M.; NICHOLS, D.; and OSYPOV, K. 2011. Building Anisotropic Models for Depth Imaging: comparing different approaches. 12th International Congress of the Brazilian Geophysical Society.

ZDRAVEVA, O.; HYDAL, S. and WOODWARD, M. 2013. Tomography with Geological Constraints - An Alternative Solution for Resolving of Carbonates. 75th Conference & Exhibition, EAGE, Extended Abstracts.

ZHAO, C.; ZDRAVEVA, O.; GONZALEZ, A.; KING, R. and GU, R. 2015. Improving interpretability of Subsalt Images by Image Conditioning and Enhancement with RTM Vector Image Partitions. 77th EAGE Conference & Exhibition, Extended Abstracts,