No-compromise marine seismic: A full-azimuth survey design for total-wavefield velocity model building and imaging in the deep-water Gulf of Mexico

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Summary

A first-ever five-vessel towed streamer configuration with all vessels participating in a simultaneous shooting scheme is presented that delivers uniformly-sampled offset-azimuth bin populations. With a maximum offset of 16 km, the survey has been designed to illuminate all potential targets below extensive and rugose salt cover in the Garden Banks and Keathley Canyon areas of the Gulf of Mexico, including ultra-deep sub-salt plays such as the BP Tiber discovery.

TTI RTM anisotropic pre-stack depth imaging of both primary and surface multiple seismic events is facilitated by true wavefield separation of dual-sensor streamer data. The latter imaging pursuit, separated wavefield imaging (SWIM) exploits subsurface sampling (illumination) substantially more dense and spatially-extensive than traditional primaries-only imaging as each of the 13,000 receivers associated with each shot become secondary sources. 18 second continuous recording will ensure several orders of multiples are recorded from all target depths. Ghost-free acquisition will also improve deep sub-salt signal penetration, whilst simultaneously providing the broadest bandwidth data required for shallow geohazard imaging.

Introduction

The seismic survey area discussed here covers about 545 OCS blocks (12,700 km^2), 390 of which are full-fold blocks, targeting the Wilcox Trend, the most active exploration play in the deep-water Gulf of Mexico (GOM), with significant recent discoveries in Keathley Canyon (Tiber, Buckskin, Moccasin and Gila), Walker Ridge (Shenandoah, Logan, Coronado and Yucatan), and Garden Banks. Other relevant discoveries occur in the Pliocene-Pleistocene (e.g. Phobos in the Sigsbee escarpment). Although the limit of this play fairway to the north and west in Garden Banks and East Breaks has not been defined, regional paleographic studies suggest that reservoir-quality Wilcox sediments were deposited in the area in a deepwater sandy fan environment.

Exploration in the western Gulf of Mexico has been hampered by industry's inability to accurately image deep structures with conventional narrow- and wide-azimuth seismic data. The geology of the region discussed here includes tight compressional folding and several levels of salt sheets, diapirs and welds. Multi-vessel survey design strategies in recent years (e.g. Moldoveanu *et al.*, 2008; Mandroux *et al.*, 2013) have identified the pursuit of very long offsets, greater than that achievable using single-vessel operations, as being a key to deep sub-salt illumination, and ideally with close to full-azimuth sampling for most offsets. The aforementioned two references highlight the diversity of survey design strategies being considered in the GOM; four or more vessels used together to increase full-azimuthal target illumination has become increasingly common, albeit with the restriction that imaging only uses primary reflections, and that each source event is recorded independently, thereby compromising inline shot sampling and data fold. To date, the only published commercial survey using several vessels with a simultaneous shooting scheme to optimize shot sampling and fold for ultra-long offset acquisition is Long *et al.* (2013).

Figure 1 illustrates how separated wavefield imaging of dual-sensor streamer data (Whitmore *et al.*, 2011) provides an opportunity to exploit the sub-salt illumination power of surface multiples during high-end imaging.

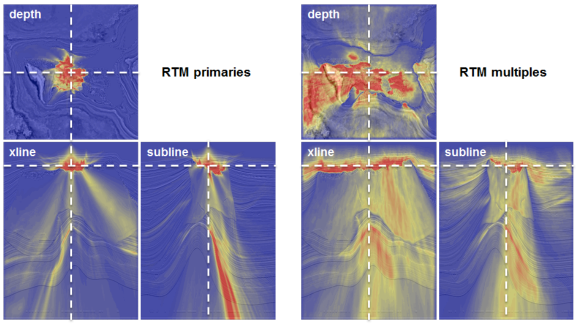

Figure 1: RTM images of a single shot within a 16 x 16 km receiver patch and for the SEAM synthetic model. Separated wavefield imaging of surface multiples (right) emphasizes the dramatic increase in spatial illumination of the subsurface in comparison to conventional imaging of primary reflections (left).

As discussed below, the inevitable ambiguities encountered when testing different wide-azimuth acquisition geometries and their associated sub-salt image quality were a motivating reason to pursue a no-compromise full-azimuth survey design exercise with multi-vessel dual-sensor streamer operations configured to meet the following objectives:

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- Uniform full-azimuthal sampling at all scales of all offsets in the range of 0-16 km to minimize imaging artifacts,
- Optimize near offset coverage, 3D shot sampling and survey fold for optimal high-end noise removal and demultiple (notably 3D SRME),
- Acquisition geometry suitable for depth velocity model building and high-end imaging pursuits, including TTI two-way anisotropic pre-stack depth imaging of both primaries and multiples.

Modeling Strategy

Governed by a local high frequency assumption that the velocity model is appropriately smooth, ray tracing will yield useful kinematic-based survey parameters such as maximum useful offset, recommended lateral 3D imaging aperture, record length, fundamental bin dimension vs. Nyquist frequency limits, etc. (Long, 2004). 3D acoustic finite difference (FD) modeling can produce realistic, full scale simulations of actual 3D seismic surveys (Regone, 2006). Because 3D FD synthetic data may be created with or without free surface multiples, and since the exact velocity model is known, it is possible to isolate the effects of acquisition geometry on image quality:

- Rapid velocity variations can be accommodated with less high frequency restriction, assuming both grid and propagation sampling is appropriately dense,
- The final images are more visually reconcilable with expected data, albeit typically with less noise associated with real world environmental and acquisition factors.

The computational cost and project turnaround overhead will inevitably be orders of magnitude higher than ray tracing-based analyses, and we observe the pursuit of rigorous quantitative analyses of such results remains a largely unrealized ambition.

Multi-Vessel Full-Azimuth Acquisition Geometry

Both FD modeling and imaging and ray tracing-based analysis were pursued with 3D models built from existing GOM 3D seismic datasets and SEAM synthetic data. Whilst a uniformly-populated rose diagram of offset-azimuth distribution for the average of all survey shot locations can be easily obtained (refer to Figure 2), and as commonly published by various authors, the design of a shooting template that delivers uniform offset-azimuth sampling between adjacent bins proved far more challenging (refer also to Long, 2010). The final shooting template established with the vessel configuration for each of the survey azimuths is shown in Figure 3.

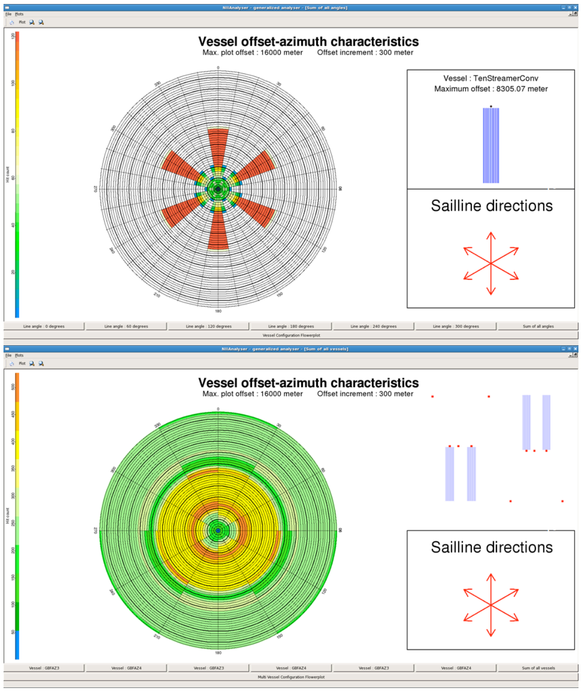

Figure 2: Rose diagram illustration of overall survey offset-azimuth distribution for single-vessel acquisition acquired in both sail-line directions for three survey azimuths (upper) and five-vessel acquisition on the full-azimuth survey template discussed here (lower). The maximum offset shown is 16 km.

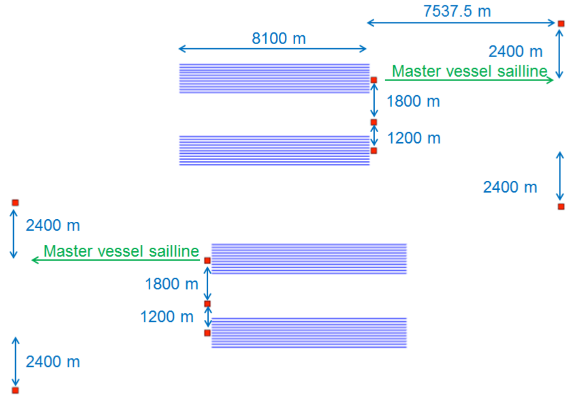

Figure 3: Five-vessel shooting geometry used for the full-azimuth survey discussed here. All five vessels tow source arrays with a simultaneous shooting scheme using all vessels. Two vessels tow 10 x 8,100 m dual-sensor streamers at 120 m separation, three survey azimuths are used: 30°, 90° and 150°. Near offset = 150 m.

The spider plot in Figure 4 reveals a desirable offset-azimuth platform for artifact-free imaging.

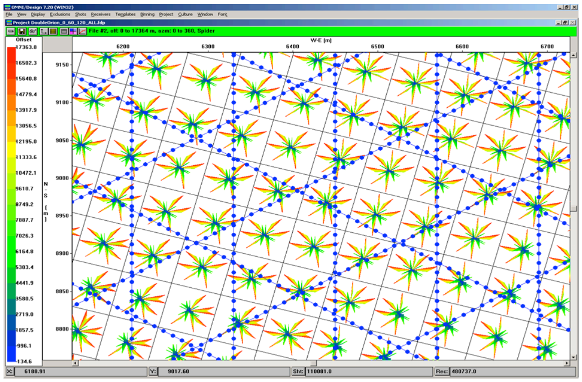
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Figure 4: Spider plot of offset-azimuth bin populations for a representative full-azimuth survey area with 60 m bin spacing. Note the uniform offset-azimuth population for each adjacent bin; critical for artifact-free imaging.

Total Wavefield Considerations

The acoustic FD modeling and imaging pursuits in the survey area discussed here comprised an intensive project. Shot gathers were modeled and imaged for various multi-vessel configurations. The five-vessel survey geometry chosen in Figure 3 was used to test and optimize processing solutions for several key considerations, including wavefield separation, simultaneous shot separation, super shot grouping, 5D regularization, wide-azimuth 3D SRME/IME, 3D tomography-based velocity model building, FWI, conventional RTM and separated wavefield imaging. Figure 5 shows an interim stage of survey planning.

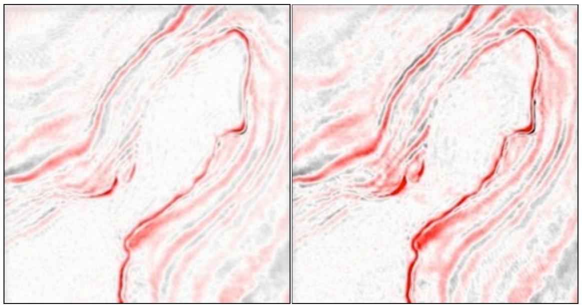

Figure 5: Example SEAM 3D model FD imaging comparison of multi-azimuth vs. larger azimuth acquisition during a stage of the survey design process. The depth slice on the right shows clearer imaging of sediments along the salt flanks.

Regards source-side and receiver-side ghost effects, dual-sensor wavefield separation (Carlson *et al.*, 2007) is a robust process that pursues a deterministic operation in the common shot domain. A custom signal processing workflow (referred to as the Bandwidth Optimized Signature Solution or BOSS+) compensates for the phase and amplitude of the bubble, the phase and amplitude of the source and instrument response, and also applies 2D angle dependent operators to compensate for the phase of the source ghost remaining after receiver-side deghosting. Consequently, source-side deghosting can be applied in a robust manner post-imaging. All relevant workflows were customized for the full-azimuth survey geometry.

Whilst the additional low frequency signal amplitudes after deghosting will expectably assist sub-salt penetration and illumination, ultra-low frequency (0-10 Hz) phase control was identified as a key outcome during survey design – to preserve AVO/AVA behavior on image gathers for subsequent inversion studies. Analysis of 3D source radiation behavior (source directivity) was also pursued to accommodate the ultra-wide cross-line offsets expected during acquisition. Single-source shooting for each vessel with 8,260 in^3 source arrays at 9 m depth was chosen with continuous recording of (nominal) 18.4 second records to optimize the capture of low frequency signals from very deep targets.

Simultaneous source separation using the inversion-based methodology described by Baardman and van Borselen (2012) was modified to accommodate the five-vessel geometry. Simultaneous shooting was designed to reduce inline shot spacing by 40% and increase overall source effort by 67%. Note that the simultaneous shooting program devised contributes significantly to the uniformity of the offset-azimuth distribution throughout the survey area (the spider plot in Figure 4) and the survey-wide offset-azimuth distribution (the rose diagram in Figure 2), particularly with respect to the enhanced contribution of larger azimuths for each sail-line orientation. Particular attention was given to low frequency amplitude preservation during source separation workflow testing, thereby complementing the deghosted output of wavefield separation applied earlier in the processing flow.

Although the subsurface illumination exploited by the separated wavefield imaging methodology is understood to benefit as the receiver array dimensions increase in all directions from each shot location (Whitmore *et al.*, 2011), the methodology had not previously been proven on real wide-azimuth data. A simplified test on existing four-vessel wide-azimuth data from the Keathley Canyon area demonstrates the anticipated improvements in imaging in various complex velocity regimes (compare Figures 6 and 7). Note that the vessel geometry in Figure 3 includes 20 streamers and therefore 13,000 receivers per shot event. Each receiver acts as a secondary source, hence the vast illumination benefits schematically illustrated in Figure 1. The one-way wave equation implementation of Whitmore

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et al. (2010) was adapted to a full TTI RTM implementation in anticipation of the survey acquisition geometry and imaging challenges discussed here.

The first-order survey planning objective, however, was to optimize all acquisition parameters to build a sufficiently accurate anisotropic (TTI) depth velocity model to image subsalt targets with conventional RTM, specifically to image the Lower Tertiary play in this area (~9-11 km deep). A secondary objective was to improve imaging above salt and deliver optimum AVO/AVA products for shallower reservoirs. Complex salt geometry is exhibited on legacy 3D seismic datasets. Whilst some areas shot good sub-salt reflectivity (e.g. near the Tiber discovery), other areas have poor reflectivity, especially in areas under adjacent juxtaposing salt wings. The depth velocity model building methodology was subsequently designed to combine best-practice TTI Beam-based and TTI RTM-based tomography (where relevant), and TTI Beam and TTI RTM imaging, complemented by high resolution TTI RTM imaging of multiples.

Conclusions

An ambitious and comprehensive survey planning effort to address sub-salt targets in the Garden Banks and Keathley Canyon areas of the Gulf of Mexico yielded a "no-compromise" five-vessel full-azimuth configuration towing dual sensor streamers. Several first-ever large-scale pursuits will be implemented:

- Simultaneous shooting with all five vessels to optimize 3D shot sampling, azimuth contribution, uniformity of offset-azimuth distribution and survey fold.
- Ultra-long offsets of 0-16 km with uniform full-azimuth sampling for all offsets, with uniform offset-azimuth sampling between adjacent bins, and 18 second record length with continuous shooting.
- Facilitation of both conventional pre-stack depth TTI RTM imaging (primaries) and high resolution TTI RTM imaging with multiples.

Both acoustic finite difference and 3D ray-tracing modeling were used extensively during survey design. In addition to isolating the effects of various acquisition geometries under consideration on image quality, the modeling results were also used to optimize low frequency content and AVO/AVA fidelity during the design of processing and imaging workflows for pursuits such as simultaneous shot separation, data regularization, multiple elimination and high-end TTI anisotropic pre-stack depth imaging of both primaries and multiples.

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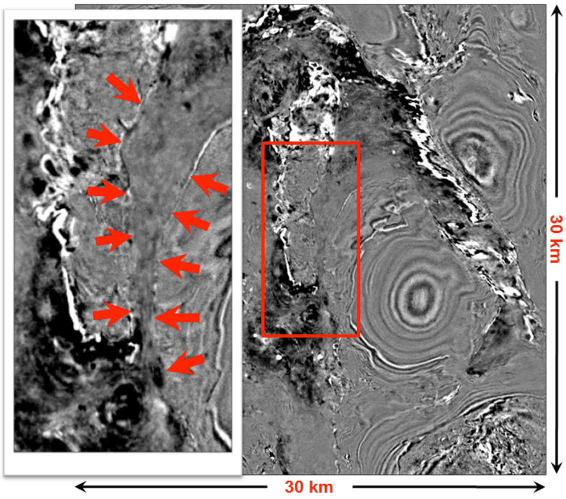

Figure 6: 3D depth slice through complex salt bodies produced by one-way wave equation pre-stack depth migration with primary reflections. Compare to Figure 7.

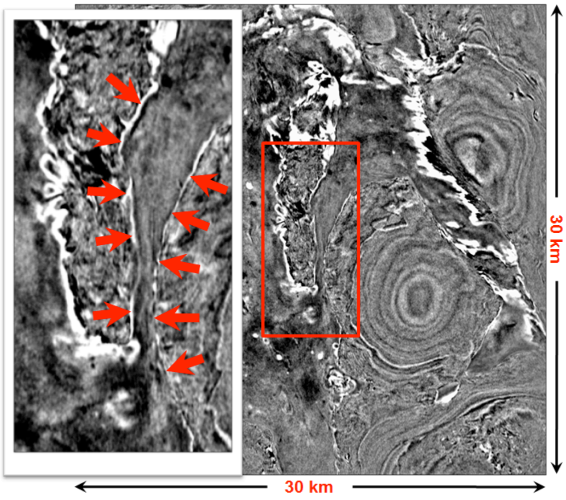

Figure 7: 3D depth slice through complex salt bodies produced by one-way wave equation pre-stack depth migration with surface multiples shows clear improvements. Compare to Figure 6.

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EDITED REFERENCES

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