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High-resolution Low-cost 3D and 4D Seismic Surveys for Deepwater Fields

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Summary

We acquired high resolution 3D and 4D streamer seismic data (HR3D and HR4D) with a small (300 cu in) air-gun source array and 18 short (100m) hydrophone cables over three deep water fields. The resulting data show that high resolution 3D images can be obtained at reservoirs located up to 2000 m below the seafloor in deepwater environments. An additional 2D test of the system demonstrated a time-lapse repeatability of NRMS=15% in zones where the reservoirs lay above the first water bottom multiple. This work suggests that HR3D surveys are suitable for low-cost time-lapse seismic monitoring of deepwater reservoirs and geohazards that are shallow relative to the water depth.

Introduction

High resolution streamer seismic surveys are frequently used in the oil and gas industry to provide detailed images of the shallow subsurface in order to better understand geo-hazards when drilling wells and planning the location of subsea infrastructure (e.g. Hill et al 2015, Brookshire et al, 2016). These surveys are typically acquired with a small source and a short streamer cable over small areas of interest compared to overall field dimensions.

HR3D streamer seismic systems employ up to 18 short hydrophone cables such as the P-Cable system (Planke et al., 2007;) shown in Figure 1. The advantage of this layout is that a wide swath of common midpoints (CMPs) is acquired for every sail line so that these systems can acquire large areas of data economically. With the P-Cable system, the hydrophone cables are spaced at 12.5 m intervals and each has 16 groups (12 hydrophones/group) spaced at 6.25 m intervals. The nominal bin size for this configuration is 6.25 m x 3.125 m with a fold of four.

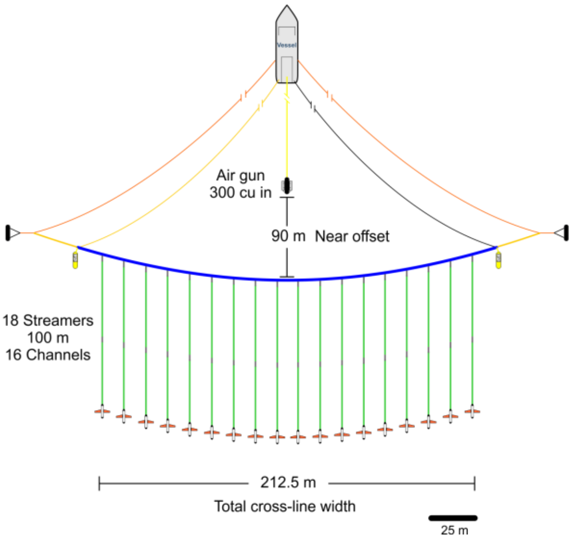

Figure 1: *The P-Cable system layout consists of vessel towing an air-gun source and 18x 100 m hydrophone cables.*

In deepwater environments, a HR3D survey contains essentially only zero-offset data acquired with a small source. It is not a technology typically considered for imaging deep reservoirs because its limited offset range means that HR3D: 1) has no ability to suppress multiples via offset stacking; 2) has no ability to undershoot shallow attenuating bodies; and 3) is not useful for deriving velocity models using conventional semblance analysis. There is also the expectation that the small source size (typically 200 – 300 cu in) will not permit sufficient depth of penetration into the subsurface.

The issue of multiple suppression becomes less-important if we apply this technology to image reservoirs that are shallower than the first water bottom multiple. We also expect to find that multiple-removal techniques like SRME will work well on densely acquired zero-offset data. The velocity model can be inherited from a conventional seismic data volume since we intend to use the HR3D for monitoring in fields that have legacy seismic available. As to the source size, recent work by Chalenski et al (2016) shows that small sources (as low as 360 cu in) can monitor deep reservoirs using a permanent reservoir monitoring (PRM) system.

To test whether the HR4D is suitable for monitoring deepwater reservoirs, we first acquired repeat 2D lines in a deepwater region of the Gulf of Mexico (GoM) and obtained an NRMS=15%. Given these excellent results we acquired baseline 3D surveys over three deepwater GoM fields to prove the imaging depth of the system and serve as baselines for future low-cost repeat surveys. Monitor 4D surveys were acquired at the end of 2017 and early 2018.

2D Repeatability tests of HR3D

To prove the repeatability of HR3D data we acquired “baseline” and (zero-time) repeat “monitor” lines over two 10km long sail-lines in the GoM. Each pair of repeat lines were co-processed as a 2D time-lapse survey. Figure 2 shows the results of this processing for one of the sail-lines. Nearly identical results were obtained from the other.

The 2D repeatability test showed that the HR3D is very repeatable. The average NRMS over the first second of data is 15% and our expectation is that for 3D data this will improve further. An NRMS repeatability of 15% is sufficient to monitor a variety of deepwater reservoirs, so we were encouraged by these results to shoot full 3D surveys as discussed in the next section.

HR3D Surveys in the Deepwater GoM

We designed surveys to image reservoirs at three fields in the GoM. Two of these fields are adjacent to one another with water depths of 2500-3000m and reservoirs located 800m – 2200m below the water bottom. All the reservoirs in this ultra-deepwater field are located above the first water bottom multiple. The third field is in 800-1200 m of water and the first of several reservoirs of interest are located 3000 m below the water bottom and all are below the first water bottom multiple.

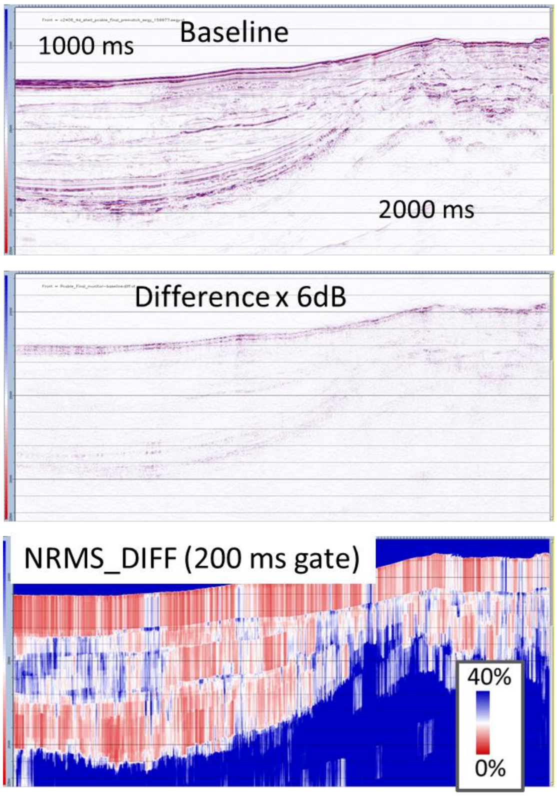

__Figure 2:__ Baseline image of a single 2D line (top), Difference between co-processed monitor and baseline scaled by 6dB (middle), NRMS of the difference (bottom) using a 200 ms gate.

We used a 300 cu in Bolt tuned airgun array comprised of 3 pairs of air guns (2x40 cu in, 2x70 cu in, 2x40 cu in) of size 1m x 6m and eighteen 100m long GeoEel solid streamer cables. We also had several PIES devices (Wang et al, 2013) placed on the seafloor in each location to measure tides and water velocities. The PIES data were uploaded acoustically at the end of each survey.

We intended to shoot the survey using a 12.5 m shot interval with the vessel sailing at a nominal speed of ~4.0 knots. This translates into a shot every 6.25 s. Given that the depth to reservoirs is greater than 4000 m, and accounting for the migration operator, the required recording time is longer than the shot interval of 6.25 s. This meant that we needed to record the data continuously during the shoot so that we could extract long shot records. This also meant that we needed to ensure that the previous shots did not interfere with the main reflectors of interest. Because of the influence of large loop currents (mesoscale eddies) during our survey, we eventually settled on shooting the data on time rather than distance, and using a staggered shot interval of ~ 6.0 s +/- 250 ms so that we could de-blend the previous shots in processing.

Processing of the HR3D data

The processing flow for the HR3D survey consists of the following steps: Data Reformat and Navigation-Merge; Trace Edits; De-blend; Application of PIES water statics; Swell Noise and Linear Noise Attenuation; Receiver Motion Correction; Shot/Channel Amplitude Scalars; Shot Receiver De-ghosting; Debubble/Designature; 3D SRME; Regularization; 3D Kirchhoff TTI PSDM; Post-Migration Stacking/Processing.

This broadband flow was designed with the potential of future repeatability studies in mind and to handle the limited offsets that were available. Figure 3 shows a full stack section before and after de-blending from 4500 ms to 8000 ms. The interfering shot energy has been removed to reveal the underlying primary energy of interest. The PIES devices produce a set of statics to address both short and long period variations in water velocity. PIES-based static estimation can be repeated for subsequent time-lapse monitor surveys. Receiver motion correction reduces time-varying positioning errors in the recorded data due to the movement of the streamers during acquisition, which will change between baseline and monitor surveys.

Due to the shallow source and receiver depths, de-ghosting is critical to recover the low frequencies. The recorded data can be related to the desired upcoming wavefield by high fidelity deterministic reflectivity operators and acoustic wave equation extrapolation operators, both of which are by nature relative amplitude preserving. The improvement in spectral content is apparent as demonstrated in Figure 4. Source signatures and bubble vary from shot to shot, for which near-field hydrophone data is used to calculate notional signatures for each shot individually. The resulting far-field source signatures will have an accurate low frequency phase that is consistent with the acquired data. This is another important consideration with respect to both repeatability and broadband processing. 3D SRME is the primary tool used to address surface multiple, as the limited offsets preclude the use of Radon de-multiple.

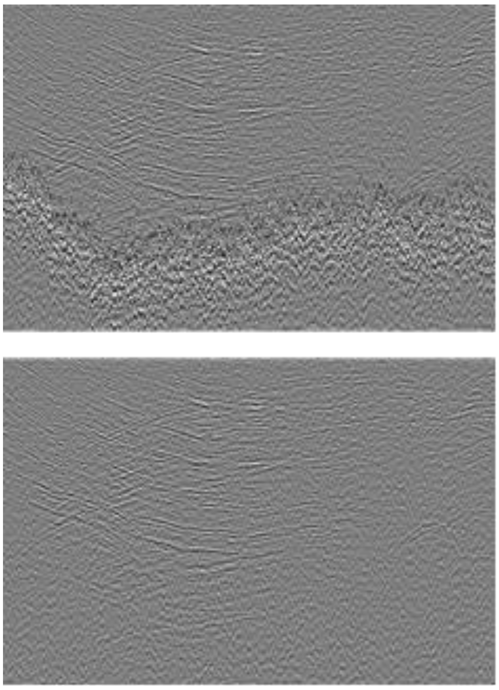

Figure 3: Un-migrated stack data before (top) and after deblending (bottom).

Results

Migrated Fast-Track PSDM images from the three fields are shown in figures 5 and 6. Despite low fold and small source size, HR3D images have good signal-to-noise ratio down to a depth of at least 2000 m from sea-floor at all the fields. HR3D is also successful in imaging targets under challenging overburden conditions - shallow attenuating zone (field 1), shale over-hang (field 2) and complex geology (field 3). The deep reflectors in HR3D images look wavy due to the zero-offset nature of HR3D survey and shallow velocity anomalies not being captured in the migration velocity model (Hatchell, 2000). However, this is not a concern as these and other illumination artifacts will be repeated in 4D. As expected, the HR3D image has very high resolution at shallow depths and is promising for monitoring shallow geo-hazards and sea-floor features. Overall, HR3D image has sufficient quality to monitor both deeper reservoir targets as well as shallow hazards.

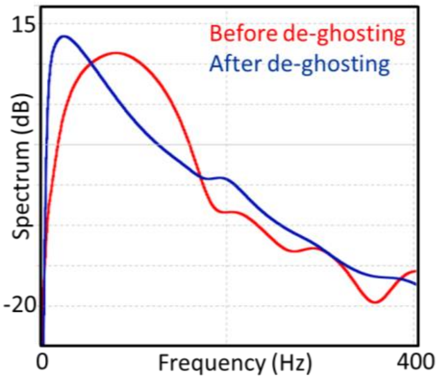

***Figure 4:** Frequcny respsponse before and after de-ghosting*

Conclusions

High resolution 3D streamer seismic surveys (HR3D) employing a small (300 cu in) air gun source array and towing 18 short (100m) hydrophone cables are found to provide good 3D images of reservoirs located 2000 m below the seafloor in deepwater environments. 2D tests of the system demonstrated a time-lapse repeatability of NRMS=15% in zones where the reservoirs lay above the first water bottom multiple. This work shows that HR3D surveys are suitable for low-cost time-lapse seismic monitoring (HR4D) of reservoirs in deepwater environments. These results justified the acquisition of 4D monitor surveys that took place at the end of 2017 and early 2018.

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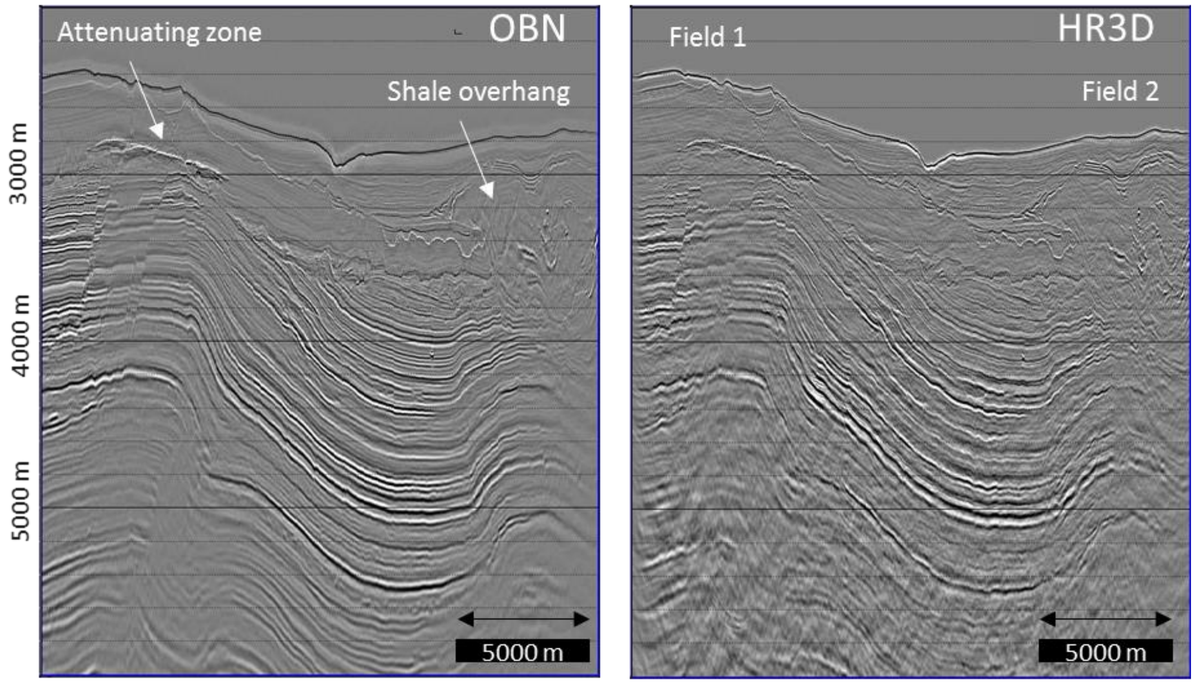

Figure 5: *3D KPSDM image from OBN (left) and fast-track HR3D (right) through fields 1 and 2.*

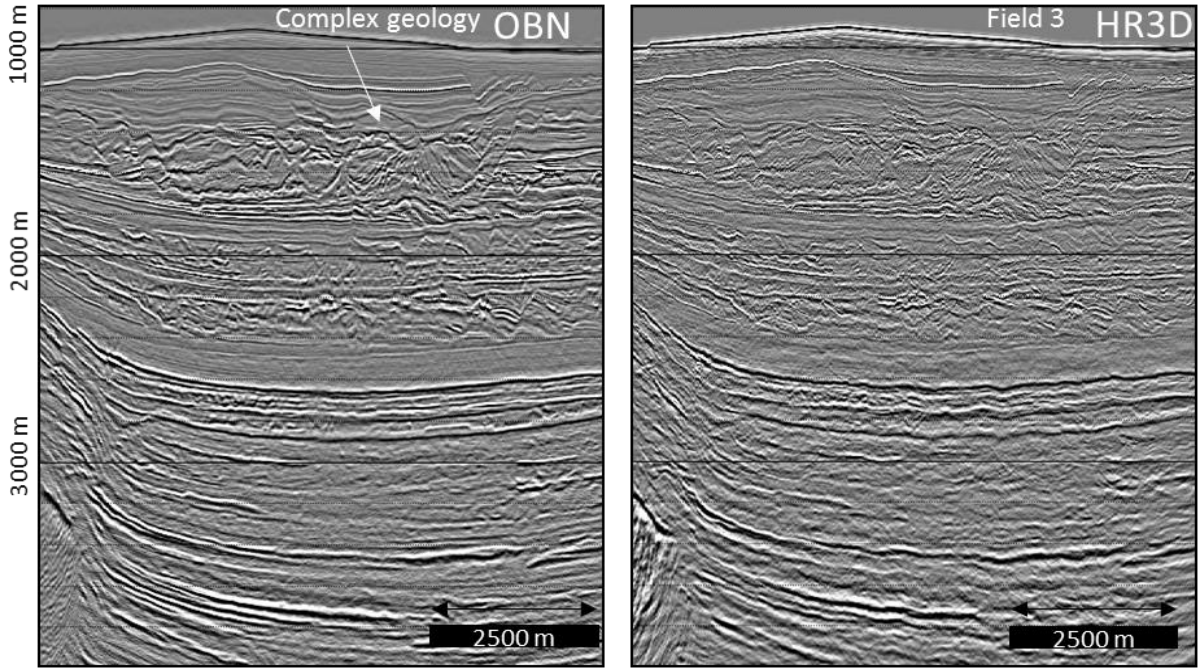

Figure 6: *3D KPSDM image from OBN (left) and fast-track HR3D (right) through field 3.*

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