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SPECIAL TOPIC

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Rapid OBN survey design using a wave equation illumination study

Jean Paul Gruffeille[1], Ayman Rehan[2], Salvador Rodriguez[1], Malcolm Lansley[3], Dave Ridyard[3*], Iulian Musat[4] present a survey design case history from the Gulf of Suez, in which a diverse and geographically distributed team of operations and geophysical experts collaborated to deliver a pragmatic solution to a complex challenge in a short time.

Rapid OBN survey design using a wave equation illumination study

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Introduction

When Neptune Energy acquired the North West Al-Amal block in the Gulf of Suez (Egypt) in 2019, the only available seismic data was a 1992 narrow azimuth towed streamer survey with offsets limited to 3000 m. Even with modern reprocessing, the deeper targets were almost completely obscured by multiple energy, and it was clear that new acquisition was required. The sub-surface challenges were compounded by surface challenges including production infrastructure, busy shipping lanes and bathymetry.

In September 2019 a survey design and optimization project, including a 3D wave equation-based illumination study was initiated. The objectives of the project were (a) to verify that a long offset, full azimuth OBN survey would solve the geophysical imaging problems and (b) to determine the most cost-effective design. The survey was successfully acquired in March 2020. This article describes the key steps in this accelerated survey design process, which was accomplished as a close (yet entirely remote) collaboration between the seven authors (and many colleagues), working for three companies in four cities, on three continents.

The sub-surface challenge

The NorthWest Al Amal block lies in the southern part of the Gulf of Suez, and the current area of interest comprises a number of prospects in a 100+sq.km. region on the eastern side of the block.

The primary geologic targets are the Nubia sandstones which are in deep faulted blocks that were created by the opening of the Red Sea. The reservoirs of interest are all below 3000 m depth.

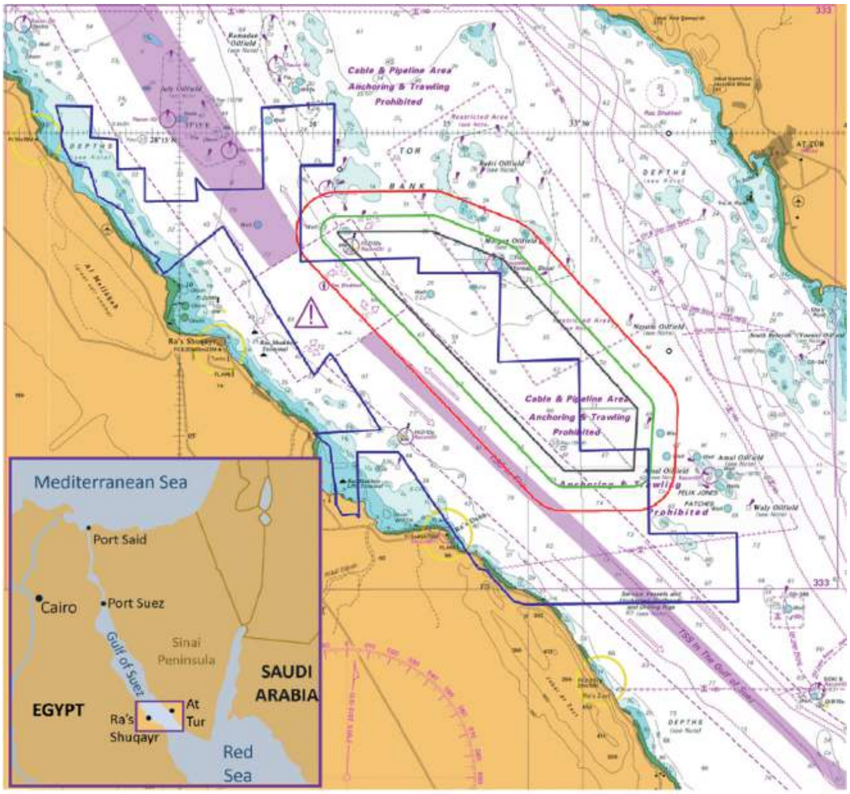

Figure 1 Location of Block 4 (blue), area of interest (black) and proposed source (red) and receiver (green) boundaries.

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The geophysical imaging challenges in this region, as described by Fattah et al[1], are considered to be among the most difficult in the world. The geology of the area is discussed more fully by Ata et al[2].

In Figure 3, we see a seismic section from legacy data that was recorded in 1992 with a narrow azimuth geometry using 5 by 3000m streamers. Thus the recorded offsets on these data are less than the depth of the objectives that are of interest today. The data shown here resulted from a Kirchhoff PSDM reprocessing project in 2017. Despite the use of modern processing algorithms these data still have significant multiple content, and very strong attenuation of the required primary reflection data because of multiple layers of shallower anhydrites and salts with high acoustic impedance contrasts. These issues cause severe difficulties for the interpreters, such as conflicts between the seismic data and well information; for example, dipmeters indicate true dips to the right, whereas seismic data shows apparent dips to the left.

True dips are revealed by the application of a dip filter (Figure 4), but image quality is poor due to the short offsets and lack of reflection energy, or signal strength, after transmission through the layers of anhydrite and salt results in a totally inadequate velocity model. Even when reflectors are visible, the structural interpretation and faulting, etc. is not reliable.

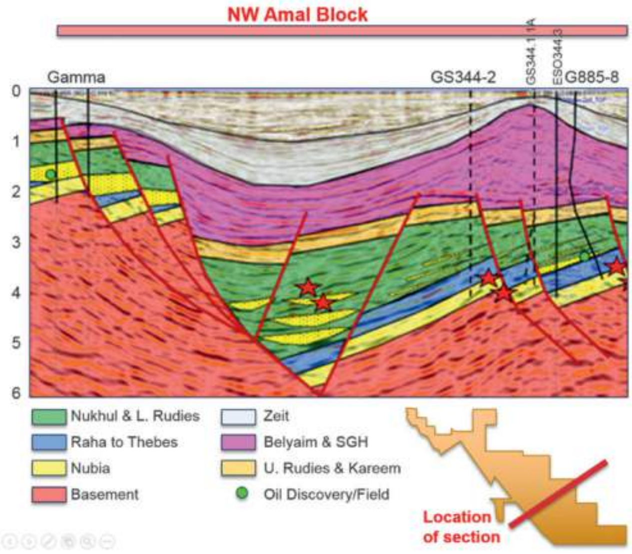


Figure 2 Geologic setting.

After significant reprocessing efforts, it was apparent that new data would be required. The working assumption at the start of the design project was that new wide azimuth, long offset data would be required to provide substantially improved imaging.

The operational challenge

The shipping lanes to the southwest and oilfield infrastructure to the north east would make this an extremely challenging survey for a multi-vessel, wide azimuth towed streamer operation, so the focus of the survey design was on a range of ocean bottom node methods.

The use of node on a rope (NOAR) acquisition made it practical and safe to acquire data around the surface obstructions, at the expense of some access limitations around the many pipelines and cables in the area.

For a relatively small survey like this, mobilization is always a significant factor in overall cost. In this case, we were fortunate that a modern and capable OBN crew was planning to operate in the adjacent block in the near future, but in order to capitalize on this opportunity, a decision on, and a design for the survey was required very rapidly.

Survey design objectives and workflow

A 3D ocean bottom seismic survey represents a significant investment. Neptune and its partners wanted some confidence that the investment would deliver a sufficient improvement in imaging quality to justify the investment. Consequently, we decided to perform an illumination study using the best available 3D model available to show the improvement in illumination from the 1992 survey to the proposed 2020 survey.

Examination of the data led us to the conclusion that full azimuth data to 6000 m offsets should be acquired, and longer offsets to 8000 m would be desirable. The question of whether adequate offsets for the use of FWI could be acquired in the time frame available received considerable discussion. It was

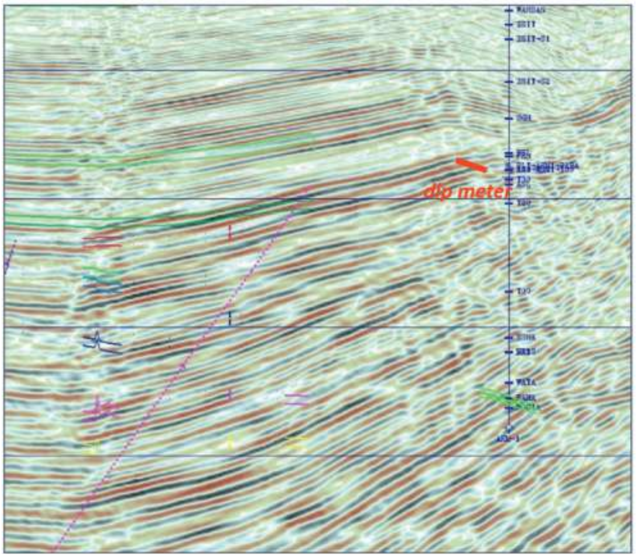


Figure 3 1992 Acquisition + 2017 Processing.

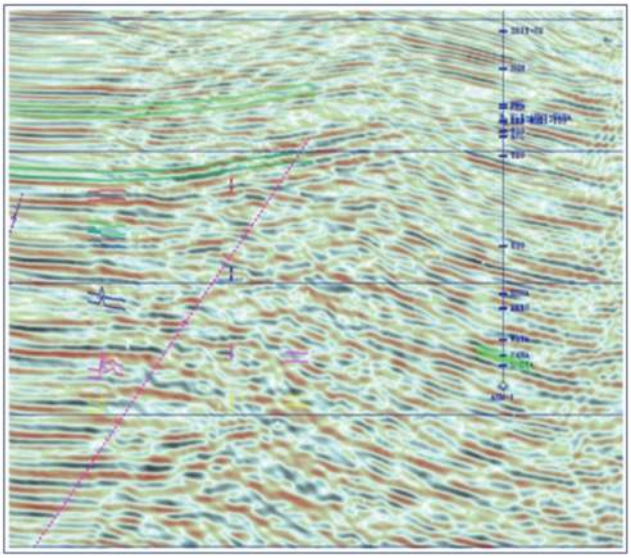


Figure 4 1992 Acquisition + 2017 Processing (dip filtered).

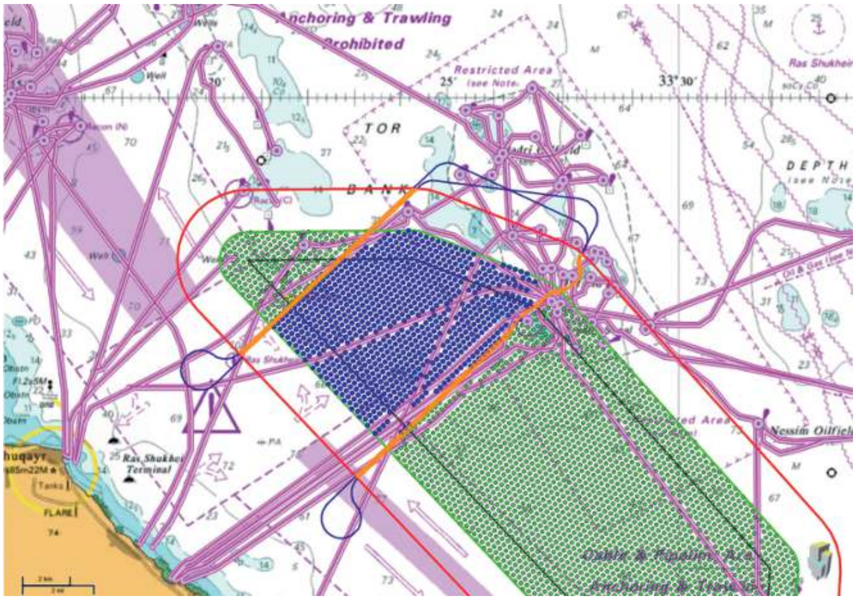


Figure 5 OBN design around obstructed area and shipping lanes, showing 200 x 200m receivers, with H pattern roll. Shots for the current patch are shown in orange, with active receivers in blue.

finally decided that with the offsets mentioned above, it would be possible to progress from refraction tomography, through reflection tomography and then FWI to resolve the complex shallow velocity field in order to perform a reliable depth migration.

A wide range of geometries were considered, and the geophysical attributes and costs estimated. Based on this initial screening, a short list of 6-8 variations was created. Due to the pressing time constraints, the illumination study was started in parallel with the detailed survey design, on the assumption that minor perturbations to the designs would not have a significant effect on the high trace density designs under consideration.

Initial geometry selection

Two things quickly became apparent as we looked at the area of interest. Firstly, the notches in the AOI added operational and imaging complexity and yet did little to reduce cost, so the AOI was simplified as shown in Figure 6. Secondly, in order to achieve the desired offset ranges over the required aperture, the source and receiver boundaries would also need to be increased.

Table 1 shows some of the many candidate geometries that were considered. The key trade off was to achieve the desired trace density with the right offset and azimuth distribution, at the lowest cost. In the table, ‘days to complete’ is used as a proxy for cost. Note that the crew available in the area had about 3000 nodes, which further narrowed the practical options.

In order to reduce the number of active nodes, the highest receiver density options were rejected, and a double sided ‘H’ pattern adopted for rolling. The final short list of basic geometries all comprised a 25m x 50m shot grid with a number of variable density receiver geometries, all using staggered grids of 100m x 200m or 200m x 200m.

Figure 6 Modified Area of Interest, and proposed Source/Receiver boundaries.

	Node spacing inline	Node spacing crossline	Number of Source arrays	Highest active node count	Trace density X <= 6000m (millions of traces/km^2 approx)	Nominal days to complete
Original AOI	50	300	Dual	4047	5.1	24
	50	300	Triple	4047	5.1	16
	200	200	Dual	1477	1.9	24
	200	200	Triple	1533	1.9	16
	100	200	Dual	2966	3.8	24
	100	200	Triple	3079	3.8	16
Modified AOI	50	300	Dual	5416	5.1	24
	50	300	Triple	5416	5.1	17
	200	200	Dual	1978	1.9	25
	200	200	Triple	2057	1.9	19
	100	200	Dual	3971	3.8	25
	100	200	Triple	4128	3.8	20

Table 1 A sample of geometries considered.

Mode converted shear wave considerations

The primary objective of the project was to achieve high-quality P-wave imaging. However, the team felt that shear waves could offer future value in reservoir characterization, so we briefly reviewed issues relating to the acquisition of mode converted shear waves.

Figure 7 shows a dipole sonic log which was used to estimate the Vp/Vs ratio. A Vp/Vs ratio of 1.7 was used in all the PS binning analysis.

One concern that was raised was that in the triple source scenario, the mode converted PS wave arrival from the target would be almost co-incident with the first arrivals from the next shot. However, it was believed that modern de-blending techniques, such as those described by Walker et al[3], could handle this situation, and the 33% reduction in cost offered by triple source on this source vessel limited project proved too attractive.

Detailed design

After simulating the effects of hazard avoidance for both the source and receiver vessel, the coverage was evaluated. Note that the coverage evaluation calculated sample points using the source and receiver elevations. For the shallow water depths on this project (70-80m) this is not a major factor, but it is a very significant factor in deep-water OBN design.

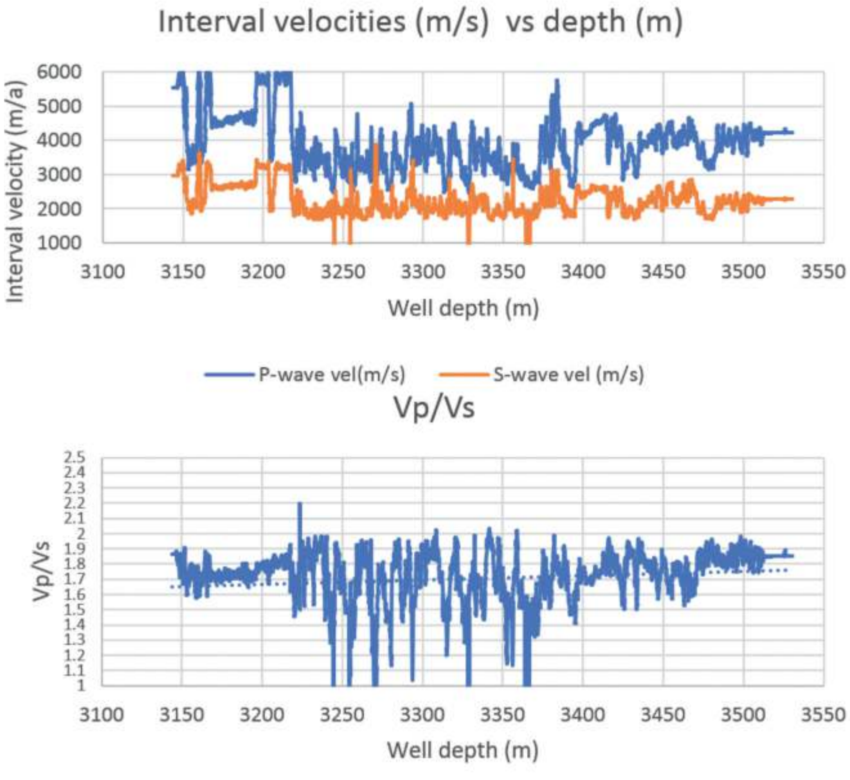


Figure 7 P and S velocities from borehole.

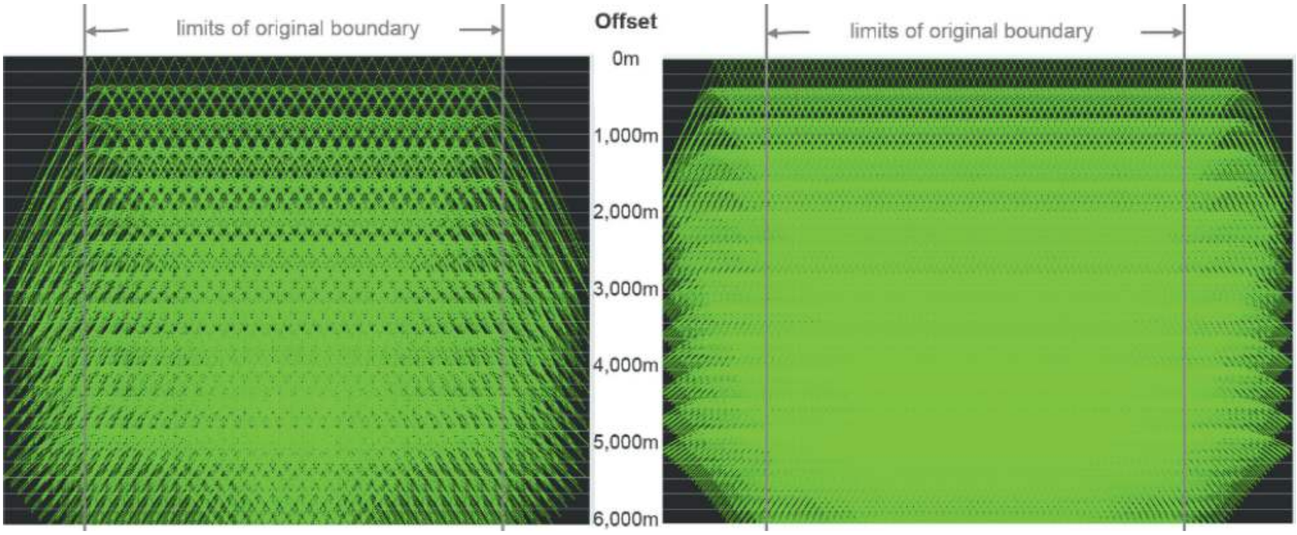


Figure 8 Offset distribution (Nominal geometries). Left: Original boundary : 200 x 200m node grid. Right: Modified boundary : 200 x 100m node grid.

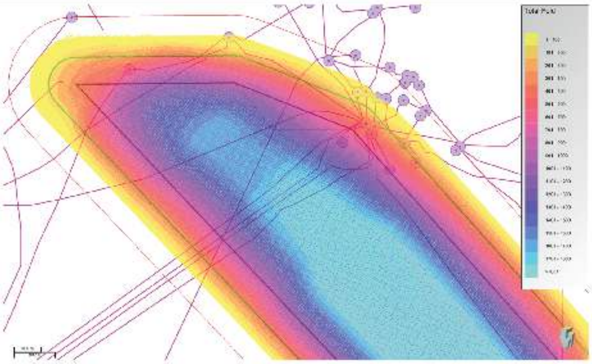
Figure 8 illustrates our key choice between using our fixed inventory of nodes to increase the area of coverage with a sparser receiver grid, or increase the trace density over a reduced area. Increasing the imaging aperture won this argument, and in fact we further extended the coverage area by shooting on line changes, as shown in Figure 9(b). Note that shooting on line changes significantly extends the high fold ridge down the central area of the project. However, real coverage obtained from shooting online turns can be slightly unpredictable and potentially lower than predicted here, due to potential loss of shots due to source maintenance.

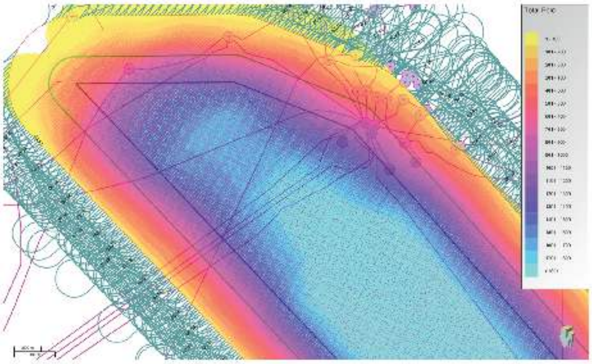
Overall PP fold and trace density remained satisfactory after hazard avoidance, but we also looked at the minimum offset coverage in each bin shown in Figure 10. In spite of the significant number of obstructions in the area, the short offset coverage was deemed adequate for all the deeper horizons, though imaging the shallow Zeit horizon could be difficult in the obstructed area. The use of a ministreamer towed behind each source was considered but rejected (a) due to the logistical challenges of procuring the streamers at short notice and (b) because the ministreamers would reduce the manoeuvrability of the source vessel, potentially making the short offset coverage holes worse.

We also looked at the impact of imaging with multiples. Imaging with multiples can be expected to deliver enhanced S/N, but in these shallow waters there was little uplift to the spatial coverage from imaging with multiples.

The mode converted coverage indicates some ‘striping’, but none of the pathologies experienced sparser receiver geometries.

Finally, detailed timing was computed for our chosen geometry, and operational issues such as node/rope inventory management and node/battery time on the seafloor were considered and validated.


(a) PP Fold


(b) PP Fold with shooting on line changes

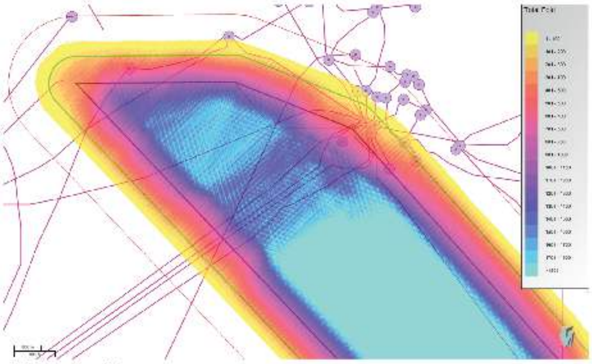

(c) PS Fold

Figure 9 Elevation corrected fold plots for 200m x 200m Rx grid.

Illumination study method

As soon as the shortlist of geometries was identified, in parallel with the detailed survey design, the illumination study was initiated. The primary goal of the study was to validate the notion that the long offset wide azimuth OBN survey would deliver

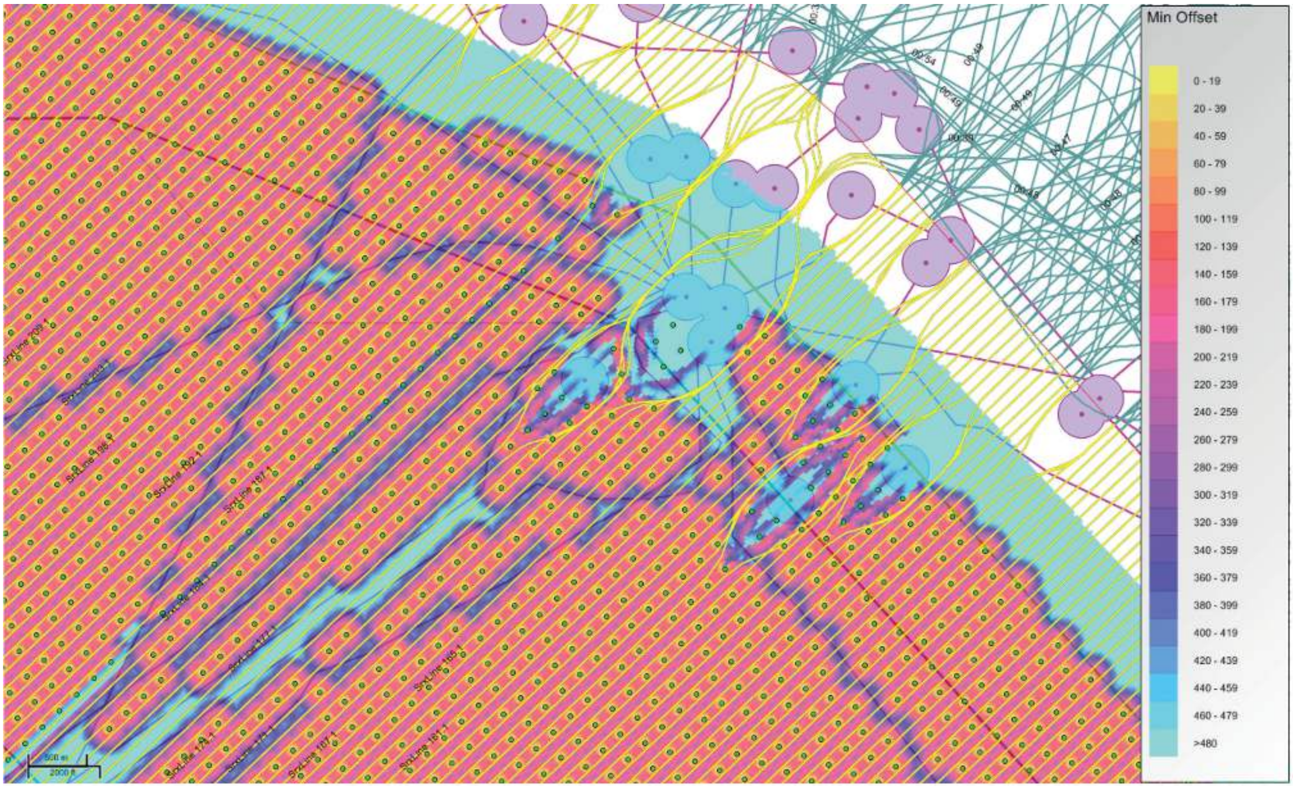


Figure 10 Minimum offset plot for 200m x 200m Rx grid (Source lines shown in yellow).

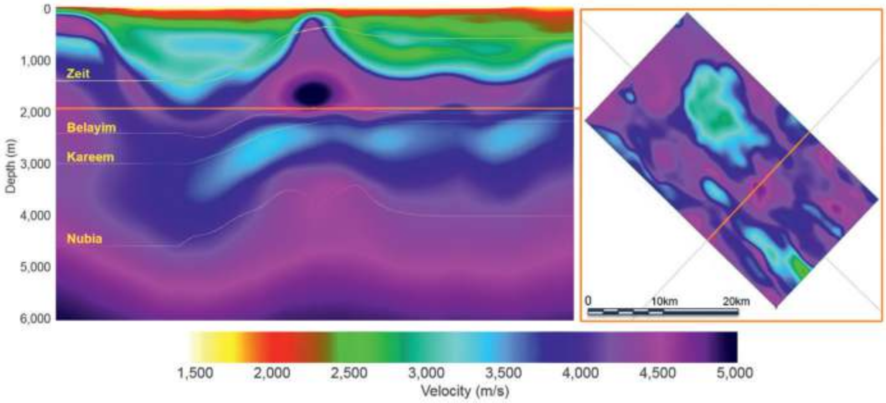


Figure 11 3D velocity model and key horizons used for illumination study.

significantly improved illumination relative to the 1992 narrow azimuth, 3000m offset streamer survey.

The 'as acquired' source and receiver geometry for the old streamer survey have become lost in the sands of time, so we used synthetic geometry with some very optimistic assumptions about zero feather angles and perfect steering. For the OBN illumination, we also used 'perfect' geometries with a 25m x 50m shot grid, and receiver geometries varying from 100m x 200m to 200m x 200m, in some cases, with denser geometries in the centre, and sparser ones at the edges.

The interval velocity-depth model for the illumination study was provided by the Neptune Energy interpreters. The illumination analysis was performed on four geologic formations with the deepest, the Nubia sandstones, being the target geologic objective

Z-Terra's illumination study technique[4,5,6] uses the simple time harmonic wave equation shown in Equation (1), with a broadband source at a known location at the surface. It is solved by downward continuation but only for a single frequency. This provides us with the wave field generated by the source at a known fixed location but just for that frequency. What is important is that this solution still incorporates all of the physics of the wave propagation including destructive and constructive interference, spherical spreading, etc. It is therefore fully wave equation consistent. Note that this method results in performance that is highly sensitive to the number of shots to be modelled. In this case, where shots outnumbered receivers by a factor of 40, we created huge efficiency by using reciprocity, and modeling receivers as shots!

$$\frac{\partial^2 u}{\partial t^2} - v^2\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = 0$$

$$u(t) = e^{i\omega t} \text{ at the source location} \qquad (1)$$

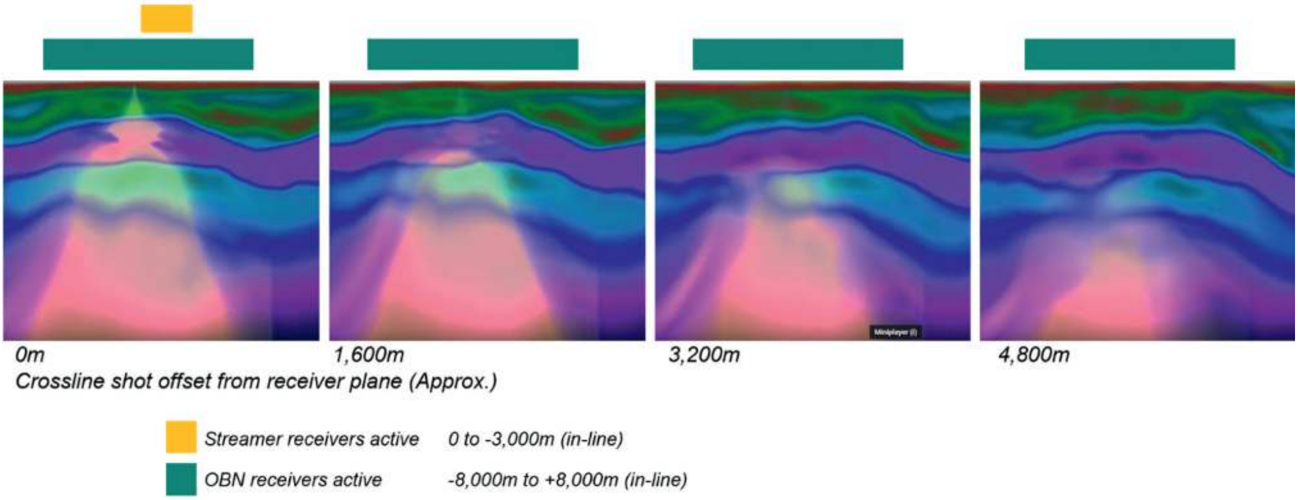


Figure 12 Downgoing source en ergy distribution.

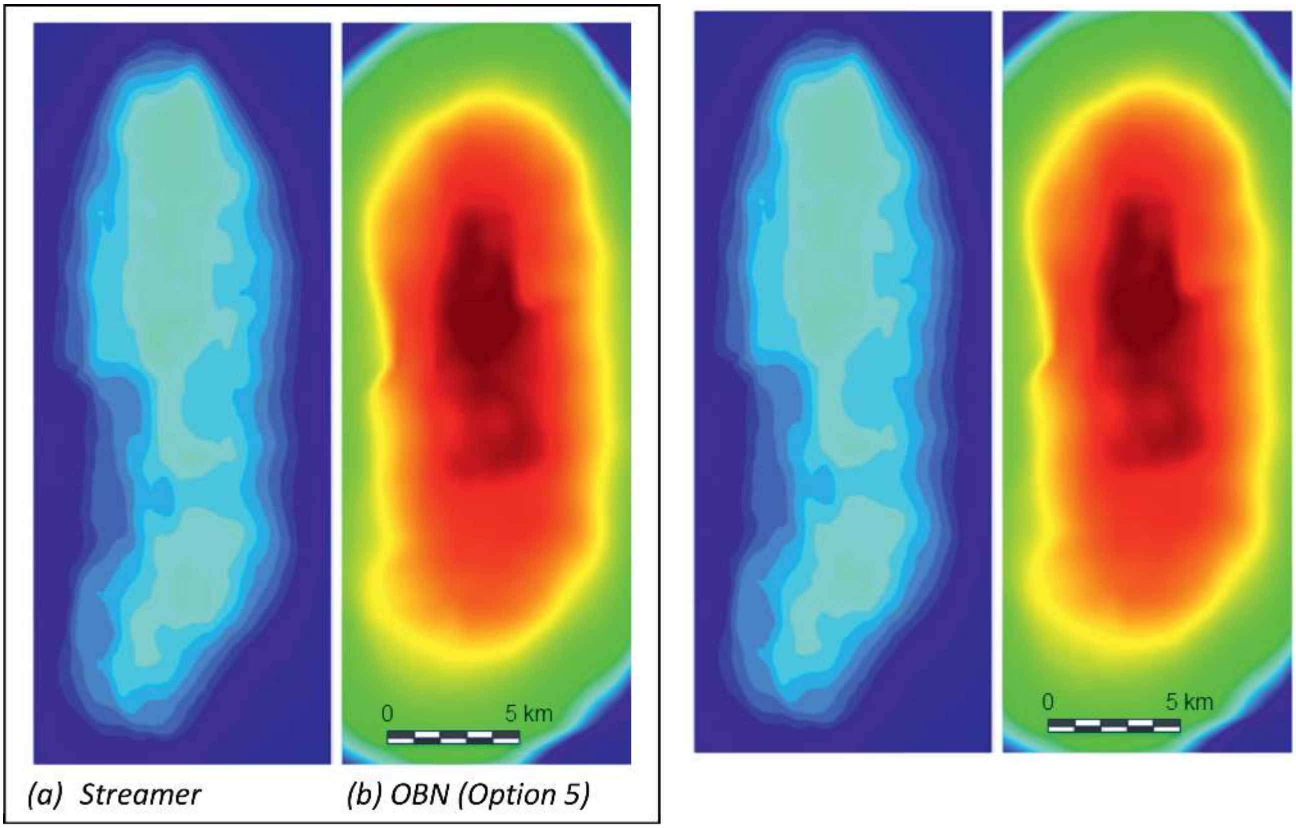


Figure 13 Illumination intensity (Deep Nubia horizon).

Illumination study results

Figure 12 illustrates why full azimuth long offset acquisition delivers enhanced illumination. These images show the downgoing source illumination for a single shot. A short offset streamer will only capture the energy returning to the surface in the plane of the shot, for receivers directly behind the vessel. However, for an OBN survey energy from a single shot location will be captured by all receivers for 360 degrees around each shot. Four representative planes are shown here, but in our proposed design, data is actually recorded on at least 60 receiver lines. This results in the desired, (and expected) massive improvement in illumination intensity shown in Figure 13. Note that these displays use the same colour scheme. The streamer illumination is low, and a significant geologic imprint is visible, whereas for the OBN survey illumination intensity is about 20 times higher, and the dominant factor in illumination is simply the trace density, which builds up systematically to a peak in the centre of the project.

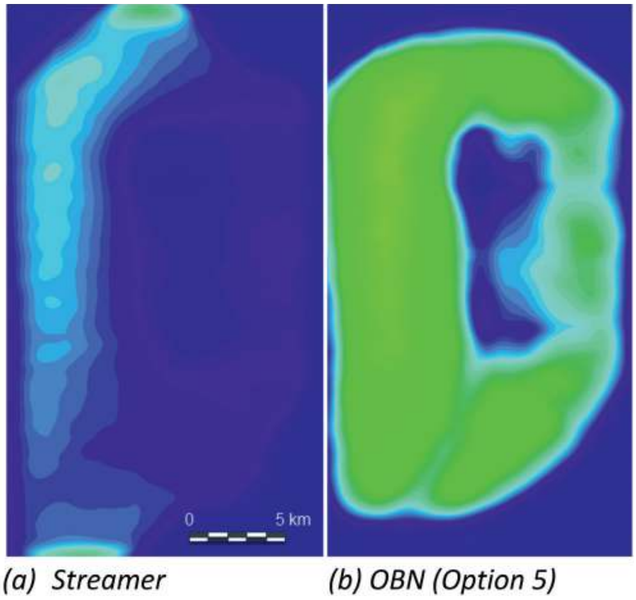
In addition to the improvement in illumination intensity, we anticipate three additional sources of improvement in signal to noise ratio.

1. Stationary point receivers will increase pre-stack S/N
2. Increased fold will improve post-stack S/N by an additional factor of about 4.5

3. Increased offset range should improve the accuracy of the velocity model, thus further improving post imaging S/N.

The wide azimuth long offset geometry shows significant advantages in illumination at all depths greater than about 1000 m. Note that for full azimuth OBN surveys, trace density is roughly proportional to the square of the maximum offset, whereas for streamer surveys, trace density is linearly proportional to the maximum offset. Thus, at very shallow depths, the advantage of the OBN geometry diminishes, and imaging the shallow Zeit horizon around the obstructed area could be challenging, particularly in the obstructed areas. As discussed earlier, a ministreamer towed at short offset behind each source could alleviate this problem, but this idea was rejected as the Zeit horizon is not a key objective.

The second phase of the illumination study was to compare the various shortlisted OBN geometries. Figure 15 demonstrates that all the wide azimuth, long offset geometries provide excellent illumination with illumination intensity increasing broadly in line with trace density.



(a) Streamer (b) OBN (Option 5)

Figure 14 Illumination intensity (Shallow Zeit horizon).

Remote collaboration

This project started in September 2019 BC (Before COVID!). In these old times, it was normal to fly stakeholders around the world to assemble in a meeting room and discuss a project. At that time, it felt like a radical idea to attempt a complex, interdisciplinary project like this using the internet to connect experts from three companies (Neptune Energy, ACTeQ and Z-Terra) in Paris, Cairo, Houston and San Francisco, using only Zoom meetings. Today we have all been forced to adopt this as a standard working practice. The authors have good news for those missing their offices and airplanes. With good will and a positive attitude, remote collaboration can deliver solid results quickly and effectively.

All the results shown here were delivered within six weeks, enabling procurement, permitting and execution of the acquisition contract to be completed within six months of the start of design.

Summary Conclusions

This was an exciting project for all involved. We had a mission, and a budget, and we are confident that we have achieved the mission within the budget.

The imaging requirements of the complex geology and the infrastructure necessitated an ocean bottom node survey. The wave equation-based PP and PS illumination study confirmed the expected benefits of the proposed new survey. Time and motion analysis gave accurate time and cost estimates for the evaluation

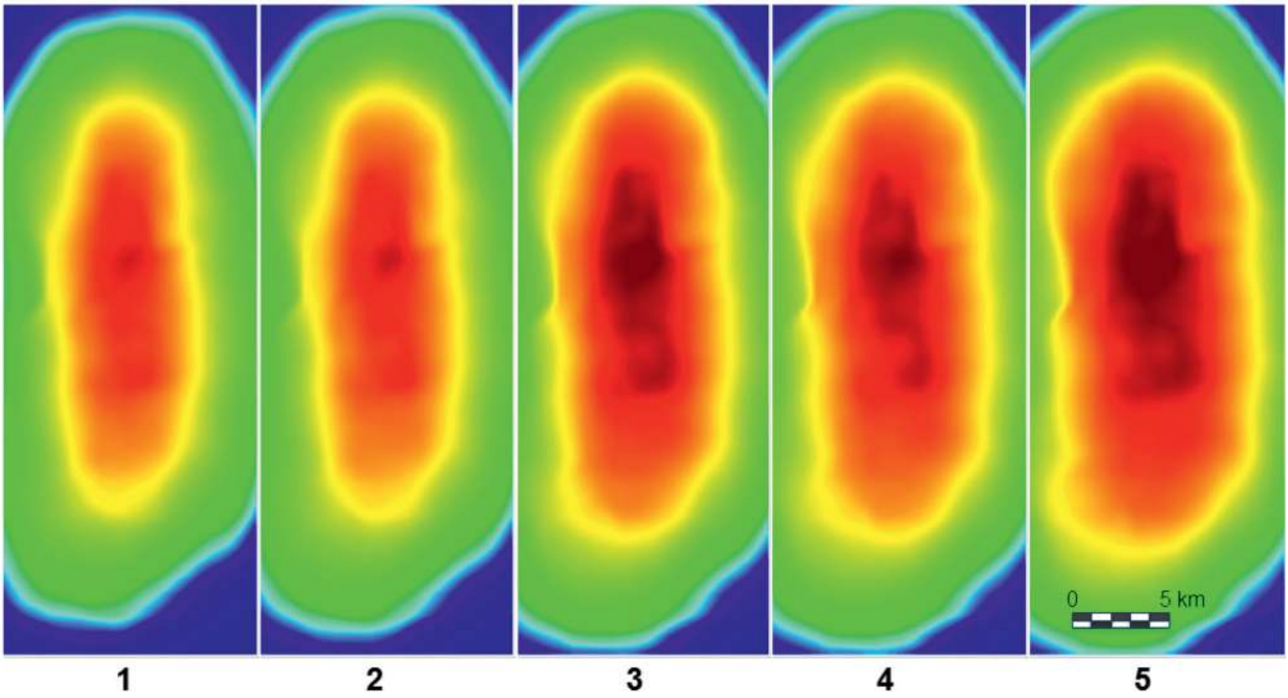


Figure 15 Illumination intensity (Deep Nubia horizon) : Increasing receiver density and area from 1-5.

of the different geometries. The actual time to acquire the survey was very close to that predicted by the planning process. The pre-planning enabled very rapid project development from initial survey design in September 2019 through the completion of the survey acquisition in April 2020.

We look forward to future publications on the acquisition, processing, imaging and interpretation of this project, and the announcement of the drilling results.

Acknowledgements

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